C++
&
Object-Oriented Programming

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C++ & Object-Oriented Programming

- Based on

  L. Ammeraal, *C++ For Programmers*, Wiley, 1994.

Abstract Data Types

- ADTs are an old concept
  - Specify the complete set of values which a variable of this *type* may assume
  - Specify completely the set of all possible operations which can be applied to values of this *type*

ISET: An ADT specification of a set type

- ISET
  - define a set type which can represent integer values
- Sets can have more than one element
  - variables of type ISET can represents several integer values simultaneously
- Sets have a number of basic operations, such as union, intersection, membership, ...

ISET: An ADT specification of a set type

- Let S denote all possible values of type ISET (i.e. sets of *integers)*
- Let *e* denote all possible values of type *integer*
- Let B denote the set of Boolean values *true* and *false*

ISET Operations

- *Syntax of ADT Operation*:

  Operation:
  WhatYouPassIt $\rightarrow$ WhatItReturns :

ISET Operations

- *Declare*: $\rightarrow$ S :

  The function value of *Declare(S)* is an empty set

  – alternative syntax: *ISET S*

ISET Operations

- *Add*: e $\times$ S $\rightarrow$ S :

  The function value of *Add(e, S)* is a set with the element *e* added

  – alternative syntax: *S2* = *S1* + *e*

ISET Operations

- *Remove*: e $\times$ S $\rightarrow$ S :

  The function value of *Remove(e, S)* is a set with the element *e* removed

  – alternative syntax: *S2 = S1 - e*

ISET Operations

- *Inclusion*: $e \times S \rightarrow B$:

  The function value of *In(e, S)* is a Boolean value
  - True if *e* is an element of *S*
  - False if *e* is not an element of *S*

  - alternative syntax: *e ? S*

ISET Operations

- *Assignment*: S $\rightarrow$ S :

  The function value of *Assign(S1, S2)* is a set with membership equal to S

  – alternative syntax: *S2* = *S1*

ISET Operations

- *Union*: $S \times S \rightarrow S$:

  The function value of *Union(S1, S2)* is a set with members those elements which are either in S1 or S2, or both

  – alternative syntax: *S3* = *S1* + *S2*

ISET Operations

- *Intersection*: $S \times S \rightarrow S$:

  The function value of *Intersection(S1, S2)* is a set with members those element which are in both S1 and S2

  – alternative syntax: *S3 = S1 . S2*

ISET Operations

- *Cardinal*: S $\rightarrow$ e :

  The function value of *Cardinal(S)* is an integer value equal to the number of elements *n* set *S*

ADT Specification

- The key idea is that we have not specified how the sets are to be implemented, merely their values and the operations to which they can be operands
- This ‘old’ idea of data abstraction is one of the key features of object-oriented programming
- C++ is a particular implementation of this object-oriented methodology

C++ Overview

- Designed by B. Stroustrup (1986)
- C++ and ANSI C (revised version of K&R C) are closely related
- Hybrid language: OO and ‘conventional’ programming
- More than just an OO version of C

Simple C++ Program

```
/* Example1: Compute the squares of both the sum and the
   difference of two given integers
*/
#include <iostream.h>
int main()
{
   cout << “Enter two integers: “; // Display
   int a, b;                       // request
   cin >> a >> b;           // Reads a and b
   int sum = a + b, diff = a - b,
       u = sum * sum, v = diff * diff;
   cout << “Square of sum       : “ << u << endl;
  cout << “Square of difference: “ << v << endl;
  return 0;
}
```

Key Points

- `/*  */`
  - begin and end of a comment
- `//`
  - beginning of a comment (ended by end of line)
- **`#include <iostream.h>`**
  - Includes the file iostream.h, a header file for stream input and output, e.g. the **<<** and **>>** operators
  - To include means to replace the include statement with the contents of the file
  - must be on a line of its own

Key Points

- In general, statements can be split over several lines
- Every C++ program contains one or more functions, one of which is called **`main`**

```
int main()      // no parameters here
  {       // beginning of body
    ...
  }       // end of body
```

- A function comprises statements which are terminated with a semi-colon

Key Points

- Declaration
  - Unlike C, a declaration is a normal statement and can occur anywhere in the function

```
int     sum = a + b, diff = a - b,
        u = sum * sum, v = diff * diff;
```

  - Declarations define variables and give them a type
  - Optionally, declarations initialize variables

Key Points

- Output to the ‘standard output stream’
  <<
- Input from the ‘standard input stream’
  >>
- Output of the end of a line is effected using the `endl` keyword
- Could also have used ‘`\n`’ or “`\n`”

Identifiers

- Sequence of characters in which only letters, digits, and underscore _ may occur
- Case sensitive ... upper and lower case letters are different

Identifiers

- Reserved identifiers (keywords):
  - `asm, auto, break, case, catch, char, class, const, continue, default, delete, do, double, else, enum, extern, float, for, friend, goto, if, inline, int, long, new operator, private, protected, public, register, return, short, switch, template, this, throw, try, typedef, union, unsigned, virtual, void, volatile, while`

Constants

- Integer constants
  - 123 (decimal)
  - 0777 (octal)
  - 0xFF3A (hexadecimal)
  - 123L (decimal, long)
  - 12U (decimal, unsigned)

Constants

- Character constants
  - ‘**A**’ enclosed in single quotes
  - Special characters (escape sequences)
    - ‘**\n**’ newline, go to the beginning of the next line
    - ‘**\r**’ carriage return, back to the beginning the current line
    - ‘**\t**’ horizontal tab
    - ‘**\v**’ vertical tab
    - ‘**\b**’ backspace
    - ‘**\f**’ form feed
    - ‘**\a**’ audible alert

Constants

- Character constants
  - ‘****’ backslash
  - ‘**\’**’ single quote
  - ‘**\”**’ double quote
  - ‘**\?**’ question mark
  - ‘***000***’ octal number
  - ‘**\x*hh***’ hex number

Constants

- Floating Constants
  - Type **`double`**

    82.247

    .63

    83.

    47e-4

    1.25E7

    61.e+4
  - Type **`float`**

    82.247L

    .63l

Constants

- Floating Constants

Type	Number of Bytes
`float`	4
`double`	8
`long double`	10

- Implementation dependent

Constants

- String Constants
  - String literal
  - String

    `“How many numbers?”`

    `“a”`
  - `“a”` is not the same as `‘a’`
  - A string is an array of characters terminated by the escape sequence `‘\0’`
  - Other escape sequences can be used in string literals, e.g. `“How many\nnumbers?”`

Constants

- String Constants
  - Concatenation of string constants

```
"How many numbers?"
```

is equivalent to

```
"How many"
    " numbers?"
```

  - This is new to C++ and ANSI C

Constants

- String Constants

```
cout << “This is a string that is \
regarded as being on one line”;
```

is equivalent to

```
cout << “This is a string that is”
        “regarded as being on one line”;
```

Comments

- `/* text of comment */`
- `//  text of comment`
- Within a comment, the characters sequences `/*`. `*/`, and `//` have no meaning

  So comments cannot be nested
- Use

```
#if 0
code fragment to be commented out
...
#endif
```

Exercises

1. Write a program that prints your name and address. Compile and run this program
2. Write a program that prints what will be your age at the end of the year. The program should request you to enter both the current year and the year of your birth
3. Modify the program to print also your age at the end of the millenium

Exercises

4. Use the operator **<<** only once to print the following three lines:

```
One double quote: “
Two double quotes: ““
Backslash: \
```

Exercises

5. Correct the errors in the following program

```
include <iostream.h>
int main();
{
   int i, j
   i = ‘A’;
   j = “B”;
   i = ‘C’ + 1;
   cout >> “End of program”;
   return 0
}
```

Expressions and Statements

- Expressions

```
a + b
x = p + q * r
```

- Statements

```
a + b;
x = p + q * r;
```

- Operators

```
+, *, =
```

- Operands

```
a, b, p, q, r, x
```

Arithmetic Operations

- Unary operator: -, +

```
neg = -epsilon;
pos = +epsilon;
```

Arithmetic Operations

- Binary operators: `+, -, *, /, %`

```
a = b + c;
```

  - Integer overflow is not detected
  - Results of division depends on the types of the operands

```
float fa = 1.0, fb = 3.0;
int a = 1, b = 3;
cout << fa/fb;
cout << a/b;
```

Arithmetic Operations

- Remainder on integer division

  %

```
39 % 5    // value of this expression?
```

Arithmetic Operations

- Assignment and addition

```
x = x + a
x += a
```

  - These are expressions and yield a value as well as performing an assignment

```
y = 3 * (x += a) + 2;  //!!!
```

Arithmetic Operations

- Other assignment operators

```
x -= a
x *= a
x /= a
x %= a

++i     // increment operator: i += 1
--i     // decrement operator: i -= 1
```

Arithmetic Operations

- Other assignment operators

```
/* value of expression = new value of i */

++i     // increment operator: i += 1
--i     // decrement operator: i -= 1

/* value of expression = old value of i */

i++     // increment operator: i += 1
i--     // decrement operator: i -= 1
```

Types, Variables, and Assignments

Type	Number of Bytes
`char`	1
`short (short int)`	2
`int`	2
`enum`	2
`long (long int)`	4
`float`	4
`double`	8
`long double`	10

Types, Variables, and Assignments

- Use **`sizeof`** to find the size of a type

  e.g.

```
cout << sizeof (double)
```

Types, Variables, and Assignments

- **<<** doesn't allow user-specified formatting of output; use (C library function) `printf`

```
char ch = 'A'; int i = 0;
float f = 1.1; double ff = 3.14159;

printf("ch = %c, i = %d\n", ch, i);
printf("f = %10f, ff = %20.15f\n", f, ff);
```

Types, Variables, and Assignments

- To use **`printf`** you must include `stdio.h`

```
#include <stdio.h>
```

- syntax:

```
printf(<format string>, <list of variables>);
```

- `<format string>`
  String containing text to be printed and conversion specifications

Types, Variables, and Assignments

- Conversion specifications

```
%c          characters
%d          decimals
%f          floats or doubles
%s          strings
```

- can also include field width specifications:

```
%m.kf       m is the field width
            k is the number of digits
            after the decimal point
```

Types, Variables, and Assignments

- **>>** doesn't allow user-specification of input types; use (C library function) `scanf`

```
char ch = 'A'; int i = 0;
float f = 1.1; double ff = 3.14159;

scanf("%c %d %f %lf", &ch, &i, &f, &ff);
```

- The ampersand `&` is essential
  - It takes the address of the variable that follows
  - scanf expects only variables

Types, Variables, and Assignments

- Enumerated types enum
  - Used to define constant values whose names mean something but whose actual values are irrelevant

```
enum days
{ Sunday, Monday, Tuesday, Wednesday,
  Thursday, Friday, Saturday
} yesterday, today, tomorrow;
days the_day_after_tomorrow;
```

  - Sunday, ..., Saturday are symbolic integer constants, have values 0, .., 6, respectively and are the values of type days

scanf(“%c %d %f %lf”, &ch, &i, &f, &ff);

Types, Variables, and Assignments

- Enumerated types example

```
today = Monday;
the_day_after_tomorrow = Tuesday;
```

- C++ has no built-in logical or Boolean type
  - We can define one using enumerated types

```
enum Boolean {FALSE, TRUE};
```

Types, Variables, and Assignments

- Register variables
  - access to data in registers is generally faster than access to data in memory
  - We can ask to compiler to put very frequently used variables in a register:

```
register int i;
```

  - Cannot take the address of a register variable

```
scanf(“%d”, &i); // illegal operation
```

Types, Variables, and Assignments

- Use the type qualifier `const` to define constants

```
const int weeklength = 7;
```

  - The initialization of weeklength is essential since we cannot assign values to constants subsequently

```
weeklength = 7; // Error
```

Comparison and Logical Operators

Operator	Meaning
<	less than
>	greater than
<=	less than or equal to
>=	greater than or equal to
==	equal to
!=	not equal to
&&	logical AND
||	logical OR
!	logical NOT

Comparison and Logical Operators

- `<, >, <=, >=` are relational operators
- `==` and `!=` are equality operators
- relational operators have a higher precedence than equality operators
- Expression formed with these operators yield one of two possible values
  - 0 means false
  - 1 means true
  - Both are of type int

Compound Statement

- Statements describe actions
- Expressions yield values
- We use braces {} to build complex - compound - statement from simpler ones
- Typically, we use compound statements in places where the syntax allows only one statement

```
{x = a + b; y = a - b;}
```

Compound Statement

- Compound statements are called blocks
- A declaration in a block is valid from the point of declaration until the closing brace of the block
- The portion of the program corresponding to this validity is called the scope of the variable which has been declared
- Variables are only visible in their scope

Compound Statement

```
// SCOPE:  Illustration of scope and visibility
#include <iostream.h>
int main()
{ float x = 3.4;
  { cout << “x = “ << x << endl;
    // output: x = 3.4 (because float x is visible
    int x = 7;
    cout << “x = “ << x << endl;
    // output x = 7 (because int x is visible
    // float x is still in scope but hidden
    char x = ‘A’;
    cout << “x = “ << x << endl;
    // output x = A (because char x is visible
    // float x and int x are still in scope but hidden
  } // end of block
```

Compound Statement

```
    cout << “x = “ << x << endl;
    // output x = 3.4 (because char x is visible
    // int x and char x are out of scope
    return 0;
} // end of main
```

Conditional Statements

- Syntax

```
if (expression)
    statement1
else
    statement2
```

  - The else clause is optional
- Semantics
  - `statement1` is executed if the value of expression is non-zero
  - `statement2` is executed if the value of expression is zero

Conditional Statements

- Where appropriate *statement1* and *statement2* can be compound statements

```
if (a >= b)
{  x = 0;
   if (a >= b+1)
   {  xx = 0;
      yy = -1;
   }
   else
   {  xx = 100;
      yy = 200;
   }
 }
```

Iteration Statements

- while-statement syntax

```
while (expression)
    statement
```

- semantics
  - `statement` is executed (repeatedly) as long as `expression` is non-zero (true)
  - `expression` is evaluated before entry to the loop

Iteration Statements

```
// compute s = 1 + 2 + ... + n

s = 0;
i = 1;
while (i <= n)
{  s += i;
   i++;
}
```

Iteration Statements

- do-statement syntax

```
do
    statement
while (expression);
```

- semantics
  - `statement` is executed (repeatedly) as long as `expression` is non-zero (true)
  - `expression` is evaluated after entry to the loop

Iteration Statements

```
// compute s = 1 + 2 + ... + n

s = 0;
i = 1;
do                      // incorrect if n == 0
{  s += i;
   i++;
} while (i <= n)
```

Iteration Statements

- for-statement

```
for (statement1  expression2; expression3)
    statement2
```

- semantics
  - *statement1* is executed
  - *statement2* is executed (repeatedly) as long as *expression2* is true (non-zero)
  - *expression3* is executed after each iteration (i.e. after each execution of *statement2*)
  - *expression2* is evaluated before entry to the loop

Iteration Statements

```
// compute s = 1 + 2 + ... + n

s = 0;
for (i = 1; i <= n; i++)
   s += i;
```

Iteration Statements

```
for (statement1  expression2; expression3)
     statement2
```

- We have *statement1* rather than *expression1* as it allows us to use an initialized declaration

  ```
  int i=0;
  ```

  - Note that the for statement does not cause the beginning of a new block (and scope) so we can only declare a variable which has not already been declared in that scope.
  - The scope of the declaration ends at the next `}`

Iteration Statements

```
// compute s = 1 + 2 + ... + n

s = 0;
for (int i = 1; i <= n; i++)
   s += i;
```

Break and Continue

- `break;`
  - the execution of a loop terminates immediately if, in its inner part, the `break;` statement is executed.

Break and Continue

```
// example of the break statement

for (int i = 1; i <= n; i++)
{  s += i;
   if (s > max_int)  // terminate loop if
      break;         // maximum sum reached
}


/* Note:  there is a much better way */
/* to write this code                */
```

Break and Continue

- `continue;`
  - the continue statement causes an immediate jump to the text for continuation of the (smallest enclosing) loop.

Break and Continue

```
// example of the continue statement

for (int i = 1; i <= n; i++)
{  s += i;
   if ((i % 10) != 0)  // print sum every
      continue;        // tenth iteration
   cout << s;
}

/* Note:  there is a much better way */
/* to write this code                */
```

Switch

- `switch (expression) statement`
  - the `switch` statement causes an immediate jump to the statement whose label matches the value of `expression`
  - `statement` is normally a compound statement with several statements and several labels
  - `expression` must be of type `int`, `char`, or `enum`

Switch

```
// example of the switch statement

switch (letter)
{  case ‘N’: cout < “New York\n”;
             break;
   case ‘L’: cout < “London\n”;
             break;
   case ‘A’: cout < “Amsterdam\n”;
             break;
   default:  cout < “Somewhere else\n”;
             break;
}
```

Switch

```
// example of the switch statement

switch (letter)
{  case ‘N’: case ‘n’: cout < “New York\n”;
                       break;
   case ‘L’: case ‘l’: cout < “London\n”;
                       break;
   case ‘A’: case ‘a’: cout < “Amsterdam\n”;
                       break;
   default:  cout < “Somewhere else\n”;
             break;
}
```

Exercises

6. Write a program that reads 20 integers and counts how often a larger integer is immediately followed by a smaller one

Conditional Expressions

- conditional expression syntax

  expression1 ? *expression2* : *expression3*

- semantics
  - if the value of *expression1* is true (non-zero)
  - then *expression2* is evaluated and this is the value of the entire conditional expression
  - otherwise *expression3* is evaluated and this is the value of the entire conditional expression

conditional expression

```
// example of the conditional expression

z = 3 * (a < b ? a + 1 : b - 1) + 2;

// alternative

if (a < b)
   z = 3 * (a + 1) + 2;
else
   z = 3 * (b - 1) + 2;
```

conditional expression

```
// example of the conditional expression

cout << “The greater of a and b is” <<
                                (a > b ? a : b);

// alternative
cout << “The greater of a and b is”
if (a < b)
   cout << a;
else
   cout << b;
```

The Comma-operator

- comma-operator syntax

  expression1 , *expression2*

- semantics
  - *expression1* and *expression2* are evaluated in turn and the value of the entire (compound) expression is equal to the value of *expression2*

The Comma-operator

```
// example of the comma operator
// compute sum of input numbers

s = 0;
while (cin >> i, i > 0)
   s += i;

// or ...
s = 0;
while (scanf (“%d”, &i), i > 0)
   s += i;
```

The Comma-operator

```
   // Note that here scanf() is used as an
   // expression and yields a value ... the
   // number of successfully-read arguments

s = 0;
while (scanf (“%d”, &i) == 1) // terminate on
    s += i;                   // non-integer
                              // input
```

Bit Manipulation

- The following bit manipulation operators can be applied to integer operands:

&	Bitwise AND
|	Bitwise OR
^	Bitwise XOR
~	Inversion of all bits
<<	Shift left
>>	Shift right

- Note, in C++, the meaning of an operator depends on the nature of its operands (cf &, <<, >>)

Simple Arrays

- The array declaration

```
int a[100]
```

enables us to use the following variables:

```
a[0], a[1], ... a[99]
```

each element being of type `int`

Simple Arrays

- subscripts can be an integer expression with value less than the array size (e.g. 100)
- In the declaration, the dimension must be a constant expression

```
#define LENGTH 100
...
int a[LENGTH]
...
for (int i=0; i<LENGTH; i++)
   a[i] = 0;  // initialize array
```

Simple Arrays

- Alternatively

```
const int LENGTH = 100;
...
int a[LENGTH]
...
for (int i=0; i<LENGTH; i++)
   a[i] = 0;  // initialize array
```

Simple Arrays

```
// LIFO: This program reads 30 integers and
// prints them out in reverse order: Last In, First Out
#include <iostream.h>
#include <iomanip.h>

int main()
{ const int LENGTH = 30;
  int i, a[LENGTH];
  cout << "Enter " << LENGTH << " integers:\n";
  for (i=0; i<LENGTH; i++) cin >> a[i];
  cout << "\nThe same integers in reverse order:\n";
  for (i=0; i<LENGTH; i++)
     cout << setw(6) << a[LENGTH - i - 1]
          << (i % 10 == 9 ? '\n' : ' ');
  return 0;
}
```

Simple Arrays

- Initializing an array

```
const int LENGTH = 4;
...
int a[LENGTH] = {34, 22, 11, 10};

int b[LENGTH] = {34, 22}; // element 2, 3 = 0

int c[20] = “Tim”;
            // same as = {‘T’, ‘i’, ‘m’, ‘\0’ }
```

Associativity

- Most operators are left-associative

```
a - b * c      //    ((a - b) * c)
               // or (a - (b * c))
```

- Right-associative operators
  - all unary operators
  - the operator `?:`, used in expressions
  - the assignment operators
    `=, +=, *=, /=, %=, &=, |=, ^=, <<=, >>=`

Associativity

- example

```
-n++    //  value for n=1? -2 or 0
```

Precedence of Operators

- operators in order of decreasing precedence (same precedence for same line)

```
() [] . -> ::
! ~ ++ + - (type) * &  sizeof new delete // all unary
.*   ->*
*   /   %
+   -
<<   >>
<   <=   >   >=
==   !=
```

Precedence of Operators

```
&
^
|
&&
||
?:
=   +=   -=   *=   /=   %=   &=   |=   ^=   <<=   >>=
,
```

Precedence of Operators

Operator	Meaning
::	scope resolution
()	function calls
[]	subscripting
.	selecting a component of a structure
->	selecting a component of a structure by means of a pointer
.*	pointers to class members
->*	pointers to class members
!	NOT, unary operator
~	inversion of all bits, unary operator

Precedence of Operators

Operator	Meaning
++	increment, unary operator
--	decrement, unary operator
+	plus, unary operator
+	addition, binary operator
-	minus, unary operator
-	minus, binary operator
(type)	cast, unary operator
new	create (allocate memory)
delete	delete (free memory)
*	‘contents of address’, unary operator
*	multiplication, binary operator

Precedence of Operators

Operator	Meaning
&	bitwise AND, binary operator
&	‘address of’, unary operator
sizeof	number of bytes inm memory, unary operator
/	division, either floating point or integer
%	remainder with integer division
<<	shift left; stream output
>>	shift right; stream input
<	less than
>	greater than
<=	less than or equal to
>=	greater than or equal to

Precedence of Operators

```
Operator    Meaning
==          equal to
!=          not equal to
^           bitwise exclusive OR (XOR)
|           bitwise OR
&&          logical AND
||          logical OR
?:          conditional expression
=           assignment
+=          addition combined with assignent
            (other operators can also be combined with
             assignment)
```

Arithmetic Conversions

- Every arithmetic expression has a type
- This type can be derived from those of its operands
  - first, integral promotion may take place: operands of type `char`, `short`, and `enum` are ‘promoted’ to `int` if this type can represent all the values of the orginal type; otherwise the original type is converted to `unsigned int`
  - type conversion is now applied, as follows

Arithmetic Conversions

- One of the following 7 rules is applied (considering each in strict order)
  - If either operand is `long double`, the other is converted to this type
  - If either operand is `double`, the other is converted to this type
  - If either operand is `float`, the other is converted to this type
  - If either operand is `unsigned long`, the other is converted to this type

Arithmetic Conversions

- One of the following 7 rules is applied (considering each in strict order)
  - If either operand is `long` and the other is `unsigned`, the other is converted to `long`, provided that `long` can represent all the values of `unsigned`. If not, both operands are converted to `unsigned long`
  - If either operand is a `long`, the other is converted to this type
  - If either operand is a `unsigned`, the other is converted to this type

The cast-operator

- Forced type conversion
  - casting
  - coercion
- `(float)n // cast n as a float (C and C++)`
- `float(n) // cast n as a float (C++)`
- Example

```
int i=14, j=3;
float x, y;
x = i/j;                    // x = 4.0
y = float(i)/float(j);      // y = 4.666..
y = float(i/j);             // y = 4.0
```

The cast-operator

- Example

```
int i;
float x = -6.9;
i = x;          // i = -6
i = int(x);     // i = -6, but it is clear
                // that conversion takes
                // place
```

Lvalues

- Consider an assignment expression of the form:

```
E1 = E2
```

- Normally `E1` will be a variable, but it can also be an expression
- An expression that can occur on the left-hand side of an assigment operator is called a *modifiable lvalue*

Lvalues

- Not lvalues:

```
3 * 5
i + 1
printf(“&d”, a)
```

- lvalues (given `int i, j, a[100], b[100];`)

```
i
a[3 * i + j]
(i)
```

Lvalues

- Array names are not lvalues:

```
a = b; // error
```

- lvalues

```
(i < j ? i : j) = 0;// assign 0 to
                    // smaller of i and j
```

  - Since `?:` has higher precedence than =, we can write as:

```
i < j ? i : j = 0;  // !!!
```

Lvalues

- The conditional expression `E1 ? E2 : E3` is an lvalue only if `E2` and `E3` are of the same type and are both lvalues
  - NB: this is a C++ feature; conditional expressions cannot be lvalues in C
- The results of a cast is not an lvalue (except in the case of reference types, yet to come)

```
float(x) = 3.14; // error
```

Functions

- In C++ there is no distinction between functions, procedure, and subroutine; we use the term function for all
- Consider a function `fun`
  - with four parameters `x, y, i,` and `j`, of type `float, float, int,` and `int`, respectively
  - which computes and returns
    - » $(x-y)/(i-j)$, $i \neq j$
    - » 10^{20}, $i = j$ and $x \neq y$ (with sign of $(x-y)$)
    - » 0, $i = j$ and $x = y$

Functions

```
// FDEMO1: Demonstration program with a function
#include <iostream.h>

int main()
{  float fun(float x, float y, int i, int j);
   float xx, yy;
   int ii, jj;
   cout << “Enter two real numbers followed by two integers:
\n”;
   cin >> xx >> yy >> ii >> jj;
   cout << “Value returned by function: “
        << fu(xx, yy, ii, jj) << endl;
   return 0;
}
```

Functions

```
float fun(float x, float y, int i, int j)
{  float a = x - y;
   int   b = i - j;
   return b != 0 ? a/b :
          a > 0  ? +1e20 :
          a < 0  ? -1e20 : 0.0;
}
```

Functions

```
float fun(float x, float y, int i, int j)//ALTERNATIVE
{  float a, result;                       //FORMULATION
   int   b;
   a = x - y;  b = i - j;
   if (b != 0)
      result = a/b;          // non-zero denominator
   else
      if (a > 0)
         result = +1e20;     // +ve numerator
      else
         if (a < 0)
            result = -1e20; // -ve numerator
         else
            result = 0.0;   // zero numerator
   return result;
}
```

Functions

- Key points
  - `fun(xx, yy, ii, jj)` is a function call
  - `xx, yy, ii, jj` are called arguments
  - the parameters `x, y, i, j` are used as local variables within the function
  - the initial values of `x, y, i, j` correspond to the passed arguments `xx, yy, ii, jj`
  - the `return` *expression*`;` statement assigns the value of expression to the function and then returns to the calling function (`main`, in this case)

Functions

- Key points
  - The type of each parameter must be specified:

```
float fun(float x, float y, int i, int j) // correct
float fun(float x, y, int i, j) // incorrect
```

  - We can omit the parameter names in the function *declaration* (but not the *definition*) but it's not good practice

```
float fun(float, float, int, int) // declaration in
                                  // main()
```

  - A function may be delared either inside a function that contains a call to it or before it at the global level

Functions

- Key points
  - A function may be delared either inside a function that contains a call to it or before it at the global level

```
float fun(float x, float y, int i, int j);
...
main()
{
}
```

  - Global declarations are valid until the end of the file
  - Can have many declarations
  - Can have only one definition (which must not occur inside another function)

Functions

- Key points
  - If the definition occurs before the first usage of the function, there is no need to declare it (as a definition is also a declaration)
  - Function arguments can be expressions

```
float result = fun(xx+1, 2*yy, ii+2, jj-ii);
```

» NOTE: the order in which the arguments are evaluated is undefined

```
/* ill defined function call */
float result = fun(xx, yy, ++ii, ii+3);
```

The `void` Keyword

- Some functions do not return a value
- Similar to procedures and subroutines
- The functions are given the type `void`

```
void max(int x, int y, int z)
{  if (y > x) x = y;
   if (z > x) x = z;
   cout << “the maximum is “ << x << endl;
}
// Poor programming style; why?
```

The `void` Keyword

- Functions with no parameters are declared (and defined) with parameters of type `void`

```
/* read a real number */
double readreal(void)
{  double x;  char ch;
   while (scanf(“%lf”, &x) != 1)
   {  // skip rest of incorrect line
      do ch = getchar(); while (ch != ‘\n’);
      printf(“\nIncorrect. Enter a number:\n”;
   }
   return x;
}
```

The `void` Keyword

- In C omission of `void` would have implied that the function could have had any number of parameters
- In C++ omission of information about parameters is not allowed
  - no parameters means NO parameters
  - `double readreal(void)` = `double readreal()`

The `void` Keyword

- In C one normally writes

```
main()
```

- This is equivalent to:

```
int main()
```

not `void main()` and implies `return 0;` at the end of the main function.

The `void` Keyword

- It makes sense to adopt the `int` formulation (with the required return `statement`) since the operating system often picks up the main return value as a run-time error code

Global Variables

- Local variables
  - defined within a function
  - visible only within that function (local scope)
- Global variables
  - defined outside functions
  - visible from the point of definition to end of the file (global scope)
  - modification of a global variable by a function is called a side-effect ... to be avoided

Global Variables

- Scope Rules
  - If two variables have the same name and are both in scope, then the one with local scope is used
- Scope resolution operator ::
  - C++ enables us to explicitly over-ride the local scope rule
  - Indicate that the global variable is meant by writing the scope-resolution-operator in front of the variable name

Scope Resolution

```
#include <iostream.h>;
int i = 1;

int main()
{  int i=2;
   cout << ::i << endl; // Output: 1 (global variable)
   cout << i   << endl; // Output: 2 (local variable)
   return 0;
}

// more on :: in the section on structures and classes
```

Functions
Altering Variables via Parameters

- C++ allows reference parameters

```
void swap1(int &x, int &y)
{  int temp;
   temp = x;
   x = y;
   y = temp;
}
```

- The arguments of `swap1` must be lvalues

Functions
Altering Variables via Parameters

- C does not allow reference parameters
- Instead of passing parameters by reference
  - we pass the address of the argument
  - and access the parameter indirectly in the function
- `&` (unary operator)
  - address of the object given by the operand
- `*` (unary operator)
  - object that has the address given by the operand

Functions
Altering Variables via Parameters

```
void swap1(int *p, int *q)
{  int temp;
   temp = *p;
   *p = *q;
   *q = temp;
}
```

- `swap(&i, &j); // function call`

Functions
Altering Variables via Parameters

- Pointers
  - `*p` has type `int`
  - But `p` is the parameter, not `*p`
  - Variables that have addresses as their values are called *pointers*
  - `p` is a pointer
  - The type of `p` is *pointer-to-int*

Functions
Types of Arguments and Return Values

- Argument Types
  - Function arguments are automatically converted to the required parameter types, if possible
  - If it is not, an (compile) error message is given
  - Thus it is valid to pass an integer argument to a function with a float parameter
  - The same rules for type conversion apply as did in assignment statements

Functions
Types of Arguments and Return Values

- Types of return values
  - The conversion rules also apply to return-statements

```
int g(double x, double y)
{  return x * x - y * y + 1;
}
```

  - Since the definition says that `g` has type `int`, the value returned is `int` and truncation take place

Functions
Types of Arguments and Return Values

- Types of return values
  - It would be better to explicitly acknowledge this with a cast

```
int g(double x, double y)
{  return int (x * x - y * y + 1);
}
```

Functions
Initialization

- Variables can be initialized when the are declared. However:
  - Variables can be initialized only when memory locations are assigned to them
  - In the absence of explicit initialization, the intial value 0 is assigned to all variables that are `global` or `static`

Functions
Initialization

-
  - `global`
    - » variables that are declared outside functions
    - » have a permanent memory location
    - » can only be intialized with a constant expression
  - `static`
    - » a keyword used in the declaration to enforce the allocation of a permanent memory location
    - » static variables local to a function are initialized ONLY the first time the function is called
    - » can only be intialized with a constant expression

Functions
Initialization

-
  - `auto`
    - » a keyword used in the declaration to enforce the (default) allocation of memory from the stack
    - » such variables are called automatic
    - » memory associated with automatic variables is released when the functions in which they are declared are exited
    - » unless initialized, you should not assume automatic variables have an initial value of 0 (or any value)
    - » can be intialized with any valid expression (not necessarily a constant expression

Functions
Initialization

```
#include <iostream.h>

void f()
{  static int i=1;
   cout << i++ << endl;
}

int main()
{  f();
   f();
   return 0;
}
```

Functions
Initialization

```
#include <iostream.h>

void f()
{  static int i=1;
   cout << i++ << endl;
}

int main()
{  f();           // prints 1
   f();           // prints 2
   return 0;
}
```

Functions
Initialization

- Uses of local static variables
  - For example, as a flag which can indicate the first time a function is called

```
void f()
{  static int first_time = 1;
   if (first_time)
   {  cout <<
      “f called for the first time\n”;
      first_time = 0;  // false
   }
   cout << “f called (every time)\n”;
}
```

Functions
Initialization

- Initialization of arrays
  - write the initial values in braces
  - There must not be more initial values than there are array elements
  - There can be fewer (but at least one!)
  - Trailing elements are initialized to 0

```
float a[a100] = {23, 41.5};
// a[0]=23; a[1]=41.5; a[2]= ... = a[99]= 0

char str[16] = “Charles Handy”;
```

Functions
Initialization

- Default arguments
  - C++ allows a function to be called with fewer arguments than there are parameters
  - Must supply the parameters with default argument values (i.e. initialized parameters)
  - Once a parameter is initialized, all subsequent parameters must also be initialized

```
void f(int i, float x=0, char ch='A')
{  ...
}
```

Functions
Initialization

```
void f(int i, float x=0, char ch='A')
{  ...
}
...
f(5, 1.23, 'E');
f(5, 1.23);  // equivalent to f(5,1.23,'A');
f(5);        // equivalent to f(5,0,'A');
```

Functions
Initialization

- Default arguments
  - functions which are both defined and declared can also have default argument
  - Default value may only be specified once, either in the declaration or in the definition

```
// declaration
void f(int i, float, char ch};

// definition
void f(int i, float x=0; char ch='A'}
{  ...
}
```

Functions
Separate Compilation

- Large programs can be split into modules, compiled separately, and subsequently linked

Functions
Separate Compilation

```
// MODULE1
#include <iostream>
int main()
{  void f(int i), g(void);
   extern int n; // declaration of n
                 // (not a definition)
   f(8);
   n++;
   g();
   cout << “End of program.\n”;
   return 0;
}
```

Functions
Separate Compilation

```
// MODULE2
#include <iostream>

int n=100;      // Defintion of n (also a declaration)
static int m=7;

void f(int i)
{  n += i+m;
}

void g(void)
{  cout << “n = “ << n << endl;
}
```

Functions
Separate Compilation

- Key points
  - `n` is used in both modules
    - » defined in module 2
    - » declared (to be extern) in module 1
  - `f()` and `g()` are used in module 1
    - » defined in module 2
    - » declared in module 1
  - A variable may only be used after it has been declared
  - Only definitions reserve memory (and hence can only be used with initializations)

Functions
Separate Compilation

- Key points
  - we defined a variable only once
  - we can declare it many times
  - a variable declaration at the global level (outside a function) is valid from that declaration until the end of the file (*global scope*)
  - a declaration inside a function is valid only in that function (*local scope*)
  - we don't need to use the keyword `extern` with functions

Functions
Separate Compilation

- Key points
  - `static int m=7;`
    - » `m` is already global and so its memory location is permanent
    - » Thus, the keyword `static` might seem unnessary;
    - » However, `static` global variables are the private to the module in which they occur
    - » cannot write

```
extern int m;  // error
```

Functions
Separate Compilation

- Key points
  - Static can also be used with functions
    - » This makes them private to the module in which they are defined
  - The keyword `static`, both for global variables and for functions, is very for
    - » avoiding name-space pollution
    - » restricting scope and usage to instances where usage is intended
    - » Avoid global variables (and make them static if you must use them)
    - » make functions static if they are private to your code

Functions
Standard Mathematical Functions

- Declare standard maths functions by

```
#include <math.h>
```

```
double cos(double x);
double sin(double x);
double tan(double x);
double exp(double x);
double ln(double x);
double log10(double x);
double pow(double x, double y); // x to the y
double sqrt(double x);
double floor(double x); // truncate
double ceil(double x);  // round up
double fabs(double x);  // |x|
```

Functions
Standard Mathematical Functions

- `double acos(double x);`
- `double asin(double x);`
- `double atan(double x); // -pi/2 .. +pi/2`
- `double atan2(double y, double x);`
- `double cosh(double x);`
- `double sinh(double x);`
- `double tanh(double x);`

- `abs and labs are defined in stdlib.h but return integer values`

Functions
Function Overloading

- C++ allows the definition of two or more functions with the same name
- This is known as *Function Overloading*
  - number or types of parameters must differ
  -
```
void writenum(int i)   // function 1
{  printf(“%10d”, i);
}

void writenum(float x) // function 2
{  printf(%10.4f”, x);
}
```

Functions
Function Overloading

```
writenum(expression);
```

- function 1 is called if expression is type int
- function 2 is called if expression is type float

- The functions are distinguished by their parameter types and parameter numbers

Functions
Function Overloading

- Allowable or not? ....

```
int g(int n)
{ ...
}

float g(int n)
{ ...
}
```

Functions
Function Overloading

- Allowable or not? ....

```
int g(int n)
{ ...
}

float g(int n)
{ ...
}
```

- Not! parameters don’t differ.

Functions
Function Overloading

- Type-safe linkage
  - Differentiation between functions is facilitated by name mangling
    - » coded information about the parameters is appended to the function name
    - » all this information is used by the linker

Functions
Function Overloading

- Type-safe linkage
  - Of use even if not using function overloading:

```
void f(float n) // definition in
{ ...           // module 1
}               // only one defn. of f

void f(int i);  // declaration in
}               // module 2
```

- C++ compilers will catch this; C compilers won't

Functions
References as Return Values

- The return value can also be a reference (just as parameters can be reference parameters)

Functions
References as Return Values

```
//REFFUN: Reference as return value.
#include <iostream.h>
int &smaller(int &x, int &y)
{  return (x < y ? x : y);
}
int main()
{  int a=23, b=15;
   cout << “a = “ << a << “ b = “ << b << endl;
   cout << “The smaller of these is “
   << smaller(a, b) << endl;
   smaller(a, b) = 0; // a function on the LHS!
   cout << “ The smaller of a and b is set to 0:”;
   cout << “a = “  << a << “ b = “ << b << endl;
   return 0;
}
```

Functions
References as Return Values

- Key points about the assignment

```
smaller(a, b) = 0;
```

- Function `smaller` returns the argument itself (i.e. either `a` or `b`)
- This gets assigned the value 0
- The arguments must be variables
- The `&` must be used with the parameters
- The returned value must exist outside the scope of the function

Functions
Inline Functions and Macros

- A call to a function causes
  - a jump to a separate and unique code segment
  - the passing and returning of arguments and function values
- This trades off time efficiency in favour of space efficiency
- Inline functions cause
  - no jump or parameter passing
  - duplication of the code segment in place of the function call

Functions
References as Return Values

```
 inline int sum(int n)
{  return n*(n+1)/2; // 1+2+ ... n
}
```

- Should only use for time-critical code
- and for short functions
- Inline functions are available only in C++, not C

Functions
Inline Functions and Macros

- In C we would have used a macro to achieve the effect of inline functions
  - define a macro
  - macro expansion occurs every time the compiler preprocessor meets the macro reference
  - for example

```
#define sum(n) ((n)*((n)+1); // note ()
```

Functions
Inline Functions and Macros

- The following macro call

```
y = 1.0 / sum(k+1)/2;
```

- expands to

```
y = 1.0 / ((k+1) * ((k+1)+1)/2);
```

Functions
Inline Functions and Macros

- If we had defined the macro without full use of parentheses

```
#define sum(n) n*(n+1)/2;
```

- the expansion would have been

```
y = 1.0 / k+1 * (k+1+1)/2;
```

- which is seriously wrong ... why?

Functions
Inline Functions and Macros

- Some macros have no parameters

```
#define LENGTH 100

#define ID_number(i) array_id[i];
```

- Since macro expansion occurs at preprocessor stage, compilation errors refer to the expanded text and make no reference to the macro definition per se

Functions
Inline Functions and Macros

```
#define f(x) ((x)*(x)+(x)+1);
...
  y = f(a) * f(b);
```

produces the syntactically incorrect code (and a possibly confusing “invalid indirection” error)

```
y = ((a)*(a)+(a)+1); * ((b)*(b)+(b)+1);;
```

Functions
Inline Functions and Macros

- Previously defined macros can be used in the definition of a macro.
- Macros cannot call themselves
  - if, in a macro definition, its own name is used then this name is not expanded

```
#define cos(x) cos((x) * PI/180)
//cos (a+b) expands to cos((a+b))*PI/180)
```

Functions
Inline Functions and Macros

- A macro can be defined more than once
  - The replacement text MUST be identical

```
#define LENGTH 100
...
#define LENGTH 1000 // not allowed
```

  - Consequently, the same macro can now be defined in more than one header file
  - And it is valid to include several such header files in the same program file

Functions
Inline Functions and Macros

- The string generating character #
  - In macro definitions, parameters immediately preceded by a # are surrounded by double quotes in the macro expansion

```
#define print_value(x) printf(#x " = %f\n", x)

...

print_value(temperature);
// expands to printf("temperature" " = %f\n",
temperature);
```

  - Consequently, the same macro can now be defined in more than one header file

Functions
Other Preprocessor Facilities

- Header files
  - The preprocessor also expands #include lines

```
#include <stdio.h>
#include “myfile.h”
```

  - The two lines are logically replaced by the contents of these header files

`<...>` search for the header file only in the general include directories

`“...”` search in the current directory first, then search in the general include direct.

Functions
Other Preprocessor Facilities

- Header files
  - normally used to declare functions and to define macros
  - included in several module files
  - header files can also include files
  - function definition should NOT be written in header files (except, perhaps, inline functions)

Functions
Other Preprocessor Facilities

- Conditional compilation
  - compile a program fragment (A) only if a certain condition is met

```
#if constant expression
    program fragment A
#else
    program fragment B
#endif
```

  - The #else clause is optional

Functions
Other Preprocessor Facilities

- Conditional compilation
  - a useful way to ‘comment out’ large sections of text which comprises statements and comments
  - (remember, we can’t nest comments)

```
#if SKIP
    /* lots of statements */
   a = PI;
   ...
#endif
```

Functions
Other Preprocessor Facilities

- Tests about names being known

```
#if !defined(PI)
#define PI 3.14159265358979
#endif
```

  - `defined()` can be used with the logical operators `!`, `||`, and `&&`

  - Older forms:

    `#ifdef` *name* is equivalent to `#if defined (`*name*`)`

    `#ifndef` *name* is equivalent to `#if !defined (`*name*`)`

Functions
Other Preprocessor Facilities

- Tests about names being known

```
#undef PI
```

undefines a name (even if it hasn’t been defined)

Functions
Other Preprocessor Facilities

- Making the compiler print error messages

```
#include “myfile.h”
#if !(defined(V_B)
#error You should use Ver. B of myfile.h
#endif
```

Compilation terminates after printing the error message

Functions
Other Preprocessor Facilities

- Predefined names
  - can be used in constant expressions

`__LINE__`	integer: current line number
`__FILE__`	string: current file being compiled
`__DATE__`	string: date in the form M*mm dd yyyy (date of compilation)*
`__TIME__`	string: date in the form M*mm dd yyyy (time of compilation)*
`__cplusplus`	a constant defined only if we are using a C++ compiler

Functions

Exercises

7. Write and test a function sort4, which has four parameters. If the integer variables a, b, c, and d are available and have been assigned values, we wish to write:

```
sort4(&a, &b, &c, &d);
```

   to sort these four variables, so that, after this call, we have a<= b <= c <= d

8. Write and test a function sort4_2 which uses reference parameters

Functions
Exercises

9. Investigate (on paper and then with a computer) the effect of the following recursive function and calling program with values k=0,1,2,...5

```
sort4(&a, &b, &c, &d);
```

Functions

Exercises

```
#include <iostream.h>
void f(int n)
{  if (n > 0)
   {  f(n-2); cout << n << " "; f(n-1);
   }
}

int main()
{  int k;
   cout << "Enter k: "; cin >> k;
   cout << "Output:\n";
   f(k);
   return 0;
}
```

Functions

Exercises

10. Write and test a (recursive) function gcd(x, y) which computes the greatest common divisor of the integers x and y. These two integers are non-negative and not both equal to zero. Use Euclid's algorithm:

```
gcd(x,y)     =     x                  if y =0
                   gcd(y, x%y)        if y!=0
```

Arrays, Pointers, and Strings
Address Arithmetic

- Address of operator &
  The value of an expression `&x` is an address
- Other expressions yield addresses
  - the name of an array, written without brackets
  - the address is that of the first element of the array

    ```
    char s[50];
    ```

    `s` is equivalent to `&(s[0])`
  - we can combine the name of an array with integers

    `s` is equivalent to `&(s[0])`

    `s+i` is equivalent to `&(s[i])`

Arrays, Pointers, and Strings
Address Arithmetic

- Such expressions are valid even when the array elements are not 1 byte in size
- In general address arithmetic takes into account the size of the element

```
int a[10];
a+i   is equivalent to   &(a[i])
```

  - Such a capability leads some people to write:

```
for (i=0; i<10; i++) scanf("%d", a+i);
```

rather than

```
for (i=0; i<10; i++) scanf("%d", &a[i]);
```

Arrays, Pointers, and Strings
Address Arithmetic

- Indirection operator *
  The value of an expression such as `*a` is the object to which the address `a` refers

`*a`	is equivalent to	`a[0]`
`*(a+i)`	is equivalent to	`a[i]`

Arrays, Pointers, and Strings
Function Arguments and Arrays

- In C and C++ there is no need for special parameter-passing for arrays
- We pass the address of the first element of the array
- Which is the array name!
- We automatically have access to all other elements in the array

Functions
Function Arguments and Arrays

```
// MINIMUM: finding the smallest element of an
// integer array

#include <iostream.h>

int main()
{  int table[10], minimum(int *a, int n);
   cout << “Enter 10 integers: \n”;
   for (int i=0; i<10; i++) cin >> table[i];
   cout << “\nThe minimum of these values is “
        << minimum(table, 10) << endl;
   return 0;
}
```

Functions
Function Arguments and Arrays

```
// definition of minimum, version A

int minimum(int *a, int n)
{  int small = *a;
   for (int i=1; i<n; i++)
      if (*(a+i) < small)
         small = *(a+i);
   return small;
}
```

Functions
Function Arguments and Arrays

```
// definition of minimum, version B (for Better!)

int minimum(int a[], int n)
{  int small = a[0];
   for (int i=1; i<n; i++)
      if (a[i] < small)
         small = a[i];
   return small;
}
```

Arrays, Pointers, and Strings
Pointers

- In the following `p` is a pointer variable

```
int *p, n=5, k;
```

- Pointers store addresses

```
p= &n;
k = *p  // k is now equal to???
```

  - `*` is sometimes known as a dereferencing operator and accessing the object to which the pointer points is known as dereferencing

```
p= &n
```

Arrays, Pointers, and Strings
Pointers

- It is essential to assign value to pointers
  - after declaring `p` we must not use `*p` before assigning a value to `p`.

```
int main()
{  char *p, ch;
   *p = 'A'; // Serious error!
   return 0;
}
```

Arrays, Pointers, and Strings
Pointers

- It is essential to assign value to pointers
  - after declaring `p` we must not use `*p` before assigning a value to `p`.

```
int main()
{  char *p, ch;
   p = &ch;
   *p = ‘A’;
   return 0;
}
```

Arrays, Pointers, and Strings
Pointers

- Pointer conversion and void-pointers

```
int i;
char *p_char;

p_char = &i; // error: incompatible types
             // pointer_to_char and
             // pointer_to_int

p_char = (char *)&i;
             // OK: casting pointer_to_int
             // as pointer_to_char
```

Arrays, Pointers, and Strings
Pointers

- In C++ we have generic pointer types: void_pointers

```
int i;
char *p_char;
void *p_void;

p_void = &i; // pointer_to_int to pointer_to_void
p_char = (char *)p_void;
             // cast needed in C++ (but not ANSI C)
             // for pointer_to_void to
             // pointer_to_int
```

Arrays, Pointers, and Strings
Pointers

- void_pointers can be used in comparisons

```
int  *p_int;
char *p_char;
void *p_void;

if (p_char == p_int) ... // Error
if (p_void == p_int) ... // OK
```

- Address arithmetic must not be applied to void_pointers. Why?

Arrays, Pointers, and Strings
Pointers

- Typedef declarations
  - used to introduce a new identifier denote an (arbitrarily complex) type

```
typedef double real;
typedef int *ptr;
...
real x,y;   // double
ptr p;      // pointer_to_int
```

Arrays, Pointers, and Strings
Pointers

- Initialization of pointers

```
int i, a[10];
int *p = &i;  // initial value of p is &i
int *q = a;   // initial value of q is the
              // address of the first element
              // of array a
```

Arrays, Pointers, and Strings
Strings

- Recap: addresses can appear in the following three forms
  - expression beginning with the & operator
  - the name of an array
  - pointer
- Another, fourth, important form which yields an address
  - A string (string constant or string literal)
  - “ABC”

Arrays, Pointers, and Strings
Strings

- “ABC”
  - effectively an array with four char elements:
  - ‘A’, ‘B’, ‘C’, and ‘\0’
  - The value of this string is the address of its first character and its type is pointer_to_char

```
*”ABC”          is equal to   ‘A’
*(“ABC” + 1)    is equal to   ‘B’
*(“ABC” + 2)    is equal to   ‘C’
*(“ABC” + 3)    is equal to   ‘\0’
```

Arrays, Pointers, and Strings
Strings

- “ABC”
  - effectively an array with four char elements:
  - ‘A’, ‘B’, ‘C’, and ‘\0’
  - The value of this string is the address of its first character and its type is pointer_to_char

```
”ABC”[0]          is equal to   ‘A’
”ABC”[1]          is equal to   ‘B’
”ABC”[2]          is equal to   ‘C’
”ABC”[3]          is equal to   ‘\0’
```

Arrays, Pointers, and Strings
Strings

- Assigning the address of a string literal to a pointer variable can be useful:

```
// POINTER
#include <stdio.h>
int main()
{  char *name = “main”;
   printf(name);
   return 0;
}
```

```
// POINTER
#include <iostream.h>
int main()
{  char *name = “main”;
   cout << name;
   return 0;
}
```

Arrays, Pointers, and Strings
Strings Operations

- Many string handling operations are declared in string.h

```
#include <string.h>

char s[4];

s = “ABC”; // Error: can’t do this in C; Why?
strcpy(s, “ABC”);  // string copy
```

Arrays, Pointers, and Strings
Strings Operations

- Many string handling operations are declared in string.h

```
#include <string.h>
#include <iostream.h>

int main()
{  char s[100]=“Program something.”, t[100];
   strcpy(t, s);
   strcpy(t+8, “in C++.”;
   cout << s << endl << t << endl;
   return 0;
}  // what is the output?
```

Arrays, Pointers, and Strings
Strings Operations

- Many string handling operations are declared in string.h

```
strnen(string);
   // returns the length of the string
E.g.
int length;
char s[100]=“ABC”;
length = strlen(s); // returns 3
```

Arrays, Pointers, and Strings
Strings Operations

- Many string handling operations are declared in string.h

```
strcat(destination, source);
   // concatenate source to destination

strncat(destination, source, n);
   // concatenate n characters of source
   // to destination
   // programmer is responsible for making
   // sure there is enough room
```

Arrays, Pointers, and Strings
Strings Operations

- Many string handling operations are declared in string.h

```
strcmp(string1, string2);
   // returns 0 in the case of equality
   // returns <0 if string1 < string2
   // returns >0 if string1 > string2

strncmp(string1, string2, n);
   // same as strcmp except only n characters
   // considered in the test
```

Arrays, Pointers, and Strings
Dynamic Memory Allocation

- Array declarations
  - require a constant length specification
  - cannot declare variable length arrays
- However, in C++ we can create an array whose length is defined at run-time

```
int n;
char *s;
...
cin >> n;
s = new char[n];
```

Arrays, Pointers, and Strings
Dynamic Memory Allocation

- If memory allocation fails
  - would have expected `new` to return a value `NULL`
  - however, in C++ the proposed standard is that instead a *new-handler* is called
  - we can (usually) force `new` to return `NULL` by calling `set_new_handler(0);` before the first use of `new`
  - This has been adopted in the Borland C++ compiler

Arrays, Pointers, and Strings
Dynamic Memory Allocation

```
// TESTMEM: test how much memory is available
#include <iostream.h>
#include <new.h> required for set_new_handler

int main()
{  char *p;
   set_new_handler(0); // required with Borland C++
   for (int i=1;;i++)  // horrible style
   {  p = new char[10000];
      if (p == 0) break;
      cout << “Allocated: “ << 10 * i << “kB\n”;
   }
   return 0;
} // rewrite this in a better style!
```

Arrays, Pointers, and Strings
Dynamic Memory Allocation

- Memory is deallocated with `delete()`
  - `p = new int // deallocate with:`
  - `delete p;`
  - `p = new int[m] // deallocate with:`
  - `delete[] p;`
  - `delete` is only available in C++

Arrays, Pointers, and Strings
Dynamic Memory Allocation

- `malloc()`
  - standard C memory allocation function
  - declared in stdlib.h
  - its argument defines the number of bytes to be allocated

```
#include <stdlib.h>
int n;
char *s;
...
cin > n;
s = (char *) malloc (n);
```

Arrays, Pointers, and Strings
Dynamic Memory Allocation

- `malloc()`
  - but to allocate an array of floats:

```
#include <stdlib.h>
int n;
float *f;
...
cin > n;
s = (float *) malloc (n * sizeof(float));
```

  - `malloc()` returns `NULL` if allocation fails

Arrays, Pointers, and Strings
Dynamic Memory Allocation

- malloc()

```
s = (float *) malloc (n * sizeof(float));
if (s == NULL)
{  cout << “Not enough memory.\n”;
   exit(1); // terminates execution of program
}           // argument 1: abnormal termination
```

Arrays, Pointers, and Strings
Dynamic Memory Allocation

- `calloc()`
  - Takes two arguments
    - » number of elements
    - » size of each element in bytes
  - all values are initialized to zero
  - `calloc()` returns `NULL` if allocation fails

Arrays, Pointers, and Strings
Dynamic Memory Allocation

- Memory is deallocated with `free()`
  - `free(s);`

Arrays, Pointers, and Strings
Input and Output of Strings

- Input

```
char[40] s;
...
scanf(“%s”, s);  // skips whitespace and terminates on
                 // whitespace
cin >> s;        // same as scanf
gets(s);         // reads an entire line

// problems if more than 40 chars are typed:
// ABCDEFGHIJKLMNOPQRSTUVWZYZabcedfghijklmnopqrstuvwzyz
// requires a string of 53 elements
```

Arrays, Pointers, and Strings
Input and Output of Strings

- Input

```
char[40] s;
...
scanf(“%39s”, s);      //reads at most 39 characters
cin >> setw(40) >> s; // same as scanf
fgets(s, 40, stdin);  // reads a line of at most 39
                      // characters, including \n
cin.getline(s, 40);   // reads a line of at most 39
                      // characters, including \n
                      // but doesn’t put \n in s
```

Arrays, Pointers, and Strings
Input and Output of Strings

- Output

```
char[40] s;
...
printf(s);              // Display just the contents of s
printf(“%s”, s);        // same
cout << s;              // same
printf(“%s\n”, s);      // Display s, followed by newline
puts(s);                // same
```

Arrays, Pointers, and Strings
Input and Output of Strings

- Output

```
// ALIGN1: strings in a table, based on standard I/O
#include <stdio.h>

int main()
{  char *p[3] = {“Charles”, “Tim”, “Peter”};
   int age[3] = {21, 5, 12}, i;
   for (i=0; i<3; i++)
      printf(“%-12s%3d\n”, p[i], age[i]); // left align
   return 0;
}
```

Arrays, Pointers, and Strings
Input and Output of Strings

- Output

```
// ALIGN2: strings in a table, based on stream I/O
#include <iostream.h>
#include <iomanip.h>
int main()
{  char *p[3] = {“Charles”, “Tim”, “Peter”};
   int age[3] = {21, 5, 12}, i;
   for (i=0; i<3; i++)
     cout << setw(12) << setiosflags(ios::left) << p[i]
          << setw(3) < resetiosflags(ios::left)
          << age[i];
return 0;
}
```

Arrays, Pointers, and Strings
Multi-Dimensional Arrays

- A table or matrix
  - can be regarded as an array whose elements are also arrays

```
float table[20][5]
int a[2][3] = {{60,30,50}, {20,80,40}};
int b[2][3] = {60,30,50,20,80,40};
char namelist[3][30]
= {“Johnson”, “Peterson”, “Jacobson”);
...
for (i=0; i<3; i++)
   cout << namelist[i] << endl;
```

Arrays, Pointers, and Strings
Multi-Dimensional Arrays

- Pointers to 2-D arrays:

```
  int i, j;
  int a[2][3] = {{60,30,50}, {20,80,40}};
  int (*p)[3]; // p is a pointer to a 1-D array
               // of three int elements
...
  p = a; // p points to first row of a
  a[i][j] = 0;          // all four statements
  (*(a+i))[j] = 0;      // are equivalent
  p[i][j] = 0;          // remember [] has higher
  (*(p+i))[j] = 0;      // priority than *
```

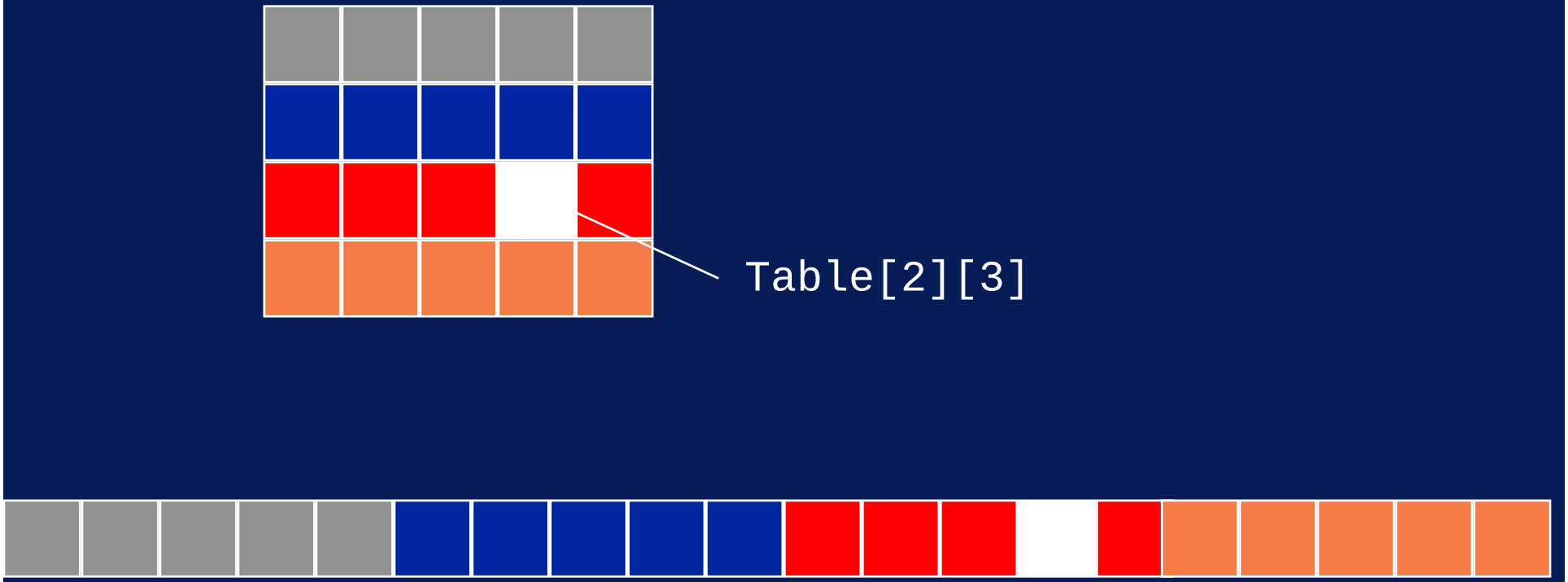
Arrays, Pointers, and Strings
Multi-Dimensional Arrays

- Function Parameters

```
int main()
{  float table[4][5];
   int f(float t[][5]);

   f(table);
   return 0;
}
int f(float t[][5]) // may omit the first dimension
{                   // but all other dimensions must
}                   // be declared since it must be
                    // possible to compute the
                    // address of each element. How?
```

Arrays, Pointers, and Strings
Multi-Dimensional Arrays



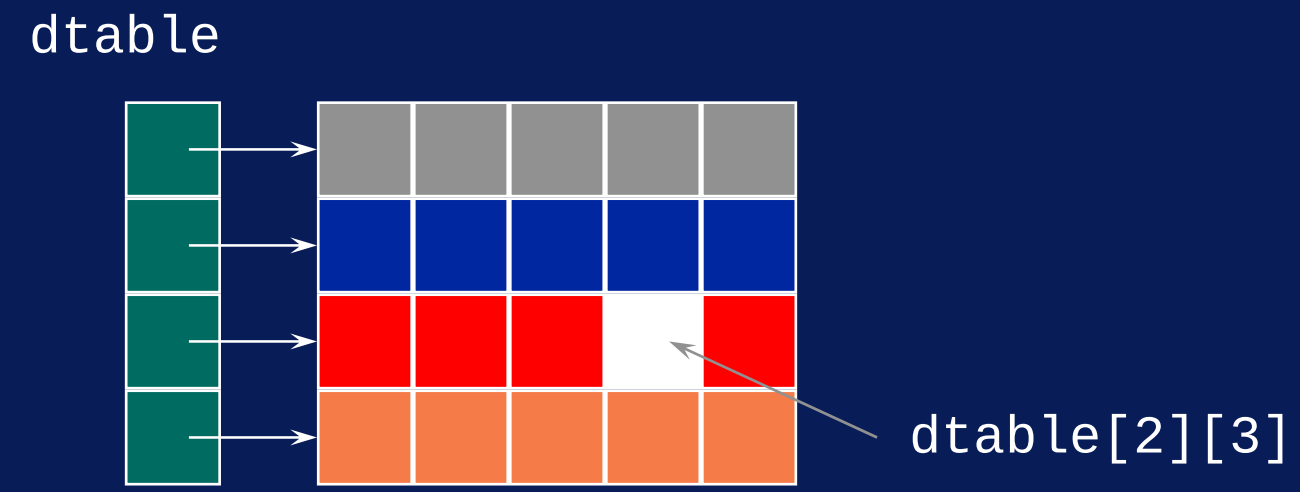
The address of Table[i][j] is computed by the mapping function 5*i + j (e.g. 5*2+3 = 13)

Arrays, Pointers, and Strings
Multi-Dimensional Arrays

- Arrays of Pointers
  - we can create 2-D ‘arrays’ in a slightly different (and more efficient) way using
    - » an array of pointers to 1-D arrays
    - » a sequence of 1-D arrays

```
float *dtable[4]; // array of 4 pointers to floats
set_new_handler(0);
for (i=0; i<20; i++)
{  dtable[i] = new float[5];
   if (dtable[i] == NULL)
   {  cout << “ Not enough memory”; exit(i);
   }
}
```

Arrays, Pointers, and Strings
Multi-Dimensional Arrays

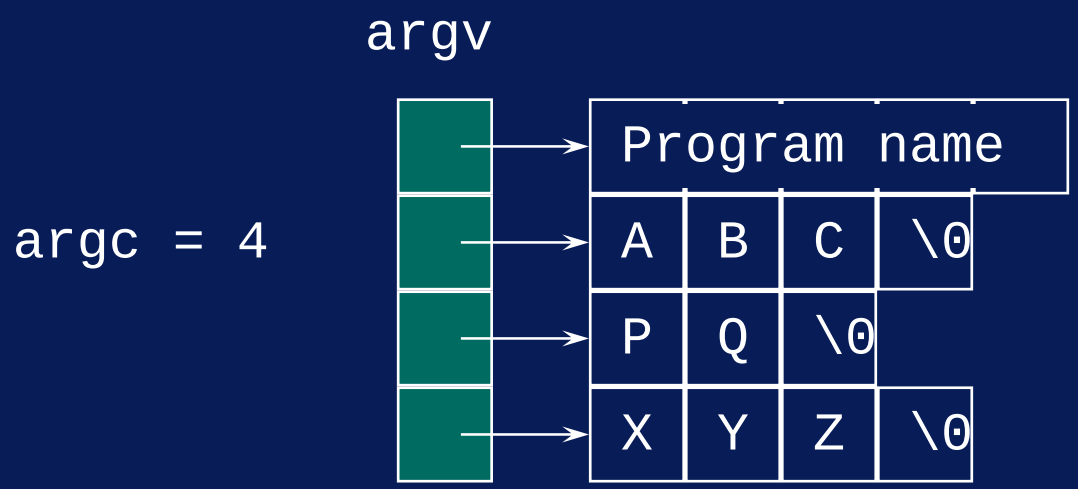


dtable[i][j] is equivalent to (*(dtable+i))[j] ...
there is no multiplication in the computation
of the address, just indirection.

Arrays, Pointers, and Strings
Program Parameters

- The main() function of a program can have parameters
  - called program parameters
  - an arbitrary number of arguments can be supplied
  - represented as a sequence of character strings
  - two parameters
    - » argc ... the number of parameters (argument count)
    - » argv ... an array of pointers to strings (argument vector)

Arrays, Pointers, and Strings
Program Parameters



Program parameters for an invocation of the form
program ABC PQ XYZ

Arrays, Pointers, and Strings
Program Parameters

```
// PROGPARAM:  Demonstration of using program parmeters
#include <iostream.h>

int main(int argc, char *argv[])
{  cout << “argc  = “ << argc << endl;
   for (int i=1; i<argc; i++)
      cout << “argv[“ << i << “]= “ << argv[i] << endl;
   return 0;
}
```

Arrays, Pointers, and Strings
In-Memory Format Conversion

- `sscanf()`
  - scans a string and converts to the designated type

```
#include <stdio.h>
...
 char s[50]="123   456 \n98.756";
 int i, j;
 double x;
 sscanf(s, "%d %d %lf", &i, &j, &x);
```

  - sscanf returns the number of value successfully scanned

Arrays, Pointers, and Strings
In-Memory Format Conversion

- `sscanf()`
  - fills a string with the characters representing the passed arguments

```
#include <stdio.h>
...
char s[50]=“123   456 \n98.756”;
sprintf(s,“Sum: %6.3f Difference:%6.3f”,
          45 + 2.89, 45 - 2.89);
```

Arrays, Pointers, and Strings
Pointers to Functions

- In C and C++ we can assign the start address of functions to pointers

```
// function definition
float example (int i, int j)
{  return 3.14159 * i + j;
}

float (*p)(int i, int j); // declaration
...
p = example;
```

Arrays, Pointers, and Strings
Pointers to Functions

- And we can now invoke the function as follows

```
(*p)(12, 34); // same as example(12,34);
```

- We can omit the * and the () to get:

```
p(12, 34);    // !!
```

- Pointers to function also allow us to pass functions as arguments to other functions

Arrays, Pointers, and Strings
Exercise

11. Write and test a function to
   - read a string representing a WWW URL (e.g. http://www.cs.may.ie)
   - replace the // with \\
   - write the string back out again

Arrays, Pointers, and Strings
Exercises

12. Write a interactive user interface which allows a user to exercise all of the set operators for three pre-defined sets A, B, and C

    Commands should be simple single keywords with zero, one, or two operands, as appropriate

    – add A 10
    – union C A B
    – list A
    – intersection C A B
    – remove 1 B

Classes and Objects
Classes and Structures

- Classes and structures - ways of grouping variables of different types
  - similar to records in other languages
  - a C++ class is a generalization of a structure in C
- C++ has both classes and structures

Classes and Objects
Classes and Structures

- Differences between Classes and C structures
  - Encapsulation
    - » classes (and C++ structures) can have functions as their members
    - » these functions operate on the data members
  - Data hiding
    - » classes provide form member-access control
    - » for each component in a class or structure we can indicate whether or not data hiding is to apply
    - » defaults:
      - class: full data-hiding
      - structure: no data-hiding

Classes and Objects
Classes and Structures

- A class is a type
  - a variable of such a type is called an object
  - (more specifically, a class object)
- Members of objects are accessed via the member names

Classes and Objects
Classes and Structures

- Example of Structure Declaration

```
struct article {
   int code;
   char name[20];
   float weight, length;
};
```

– this structure is a class with only public members

Classes and Objects
Classes and Structures

- Equivalent example of Class Declaration

```
class article {
public:
   int code;
   char name[20];
   float weight, length;
};
```

– this structure is a class with only public members

Classes and Objects
Classes and Structures

- Declaration (and definition) of a class variable (i.e. object)

```
article s, t;  // in C we would have
               // had to write
               // struct article s, t;
```

  - This form is identical to the conventional variable definitions

Classes and Objects
Classes and Structures

- Since class declarations will probably be used by many program modules, it is good practice to put them in a header file which can be included as required

```
#include “my_classes.h”
```

Classes and Objects
Classes and Structures

- Access to members of class variables

```
s.code = 123;
strcpy(s.name, “Pencil”);
s.weight = 12.3;
s.length = 150.7;
t = s;  // !! object assignment possible
        // even though a member is an
        // array (and array assignment
        // is not possible)
```

Classes and Objects
Classes and Structures

- Composite variables such as classes, structures, arrays are called aggregates
- Members of aggregrates which are in turn aggregates are called subaggregates

Classes and Objects
Classes and Structures

- Pointers to class objects

```
article *p;
...
(*p).code = 123; // normal dereferncing
p->code = 123;   // more usual shorthand
```

Classes and Objects
Classes and Structures

- Initialization of class objects

```
class article {
public:
   int code;
   char name[20;
   float weight, length;
};
int main()
{ static article s = (246, “Pen”, 20.6, 147.0},
  t;  // is t initialized?
  ...
```

Classes and Objects
Classes and Structures

- Initialization of class objects with object of identical type

```
...
article s = (246, “Pen”, 20.6, 147.0};
...

void f(void)
{ article t=s, u=t;
  ...
}
```

Classes and Objects
Classes and Structures

- Subaggregates
  - access to array members

```
s.name[3] = ‘A’; // i.e. (s.name)[3]
```

  - arrays of class objects

```
article table[2];
...
table[i].length = 0;
table[i].name[j] = ‘ ‘;
```

Classes and Objects
Classes as Arguments and Return Values

- Three possibilities
  - By ‘value’; entire class object as argument/return value
  - By address
  - By reference (effectively the same as address)
- The following three examples will use a show how a function can create a new object with values based on an object passed to it

Classes and Objects
Classes as Arguments and Return Values

- Assume the following class declaration

```
// ARTICLE.H: header file for 3 demos
class article {
public:
   int code;
   char name[20];
   float weight, length;
};
```

Classes and Objects
Classes as Arguments and Return Values

- Pass by value: copy class objects

```
// ENTOBJ: passing an entire class object
#include <iostream.h>
#include “article.h”

article largeobj(article x)   // functional spec
{  x.code++;                  // increment code
   x.weight *=2 ;             // double weight
   x.length *=2;              // double length
   return x;                  // return new obj.
}
// main to follow
```

Classes and Objects
Classes as Arguments and Return Values

- Pass by value: copy class objects

```
int main()
{  article s = (246, “Pen”, 20.6, 147.0), t;
   t = largeobj(s);
   cout << t.code << endl;
   return 0;
}
```

Classes and Objects
Classes as Arguments and Return Values

- Pass address of class object

```
// PTROBJ: pointer parameter & return value
#include <iostream.h>
#include <string.h>
#include “article.h”
article *plargeobj(article *px) // functional spec
{  article *p;                  // pointer
   p = new article;             // new article
   p->codex++;                  // increment code
   strcpy(p->name, px->name);   // copy name
   p->weight = 2 * px->weight;  // double weight
   p->length = 2 * px->length;  // double length
   return p;                    // return new obj.
}
// main to follow
```

Classes and Objects
Classes as Arguments and Return Values

- Pass address of class object

```
int main()
{  article s = (246, “Pen”, 20.6, 147.0);
   article *pt;
   pt = plargeobj(&s);
   cout << pt->code << endl;
   return 0;
}
```

Classes and Objects
Classes as Arguments and Return Values

- Pass address of class object; V.2

```
// PTROBJ2: pointer parameter
#include <iostream.h>
#include <string.h>
#include “article.h”
void penlargeobj(article *p)    // functional spec
{  p->codex++;                  // modify values
   p->weight *= 2;              // of passed
   p->length *= 2;              // object
}
// main to follow
...
penlargeobj(&s);
```

Classes and Objects
Classes as Arguments and Return Values

- Pass address of class object - common error

```
// PTROBJ: pointer parameter & return value
#include <iostream.h>
#include <string.h>
#include “article.h”
article *plargeobj(article *px) // functional spec
{  article obj;                 // local object
   obj.codex = px->code +1;     // increment code
   strcpy(obj.name, px->name);  // copy name
   obj.weight = 2 * px->weight; // double weight
   obj.length = 2 * px->length; // double length
   return &obj;                 // ERROR; WHY?
}
```

Classes and Objects
Classes as Arguments and Return Values

- Pass reference to class object

```
// REFOBJ: reference parameter & return value
#include <iostream.h>
#include <string.h>
#include “article.h”
article &rlargeobj(article &x) // functional spec
{  article *p;                  // pointer
   p = new article;             // new article
   p->codex = x.code + 1;       // increment code
   strcpy(p->name, x.name);     // copy name
   p->weight = 2 * x.weight;    // double weight
   p->length = 2 * x.length;    // double length
   return *p;                   // return new obj.
}
// main to follow
```

Classes and Objects
Classes as Arguments and Return Values

- Pass reference to class object

```
int main()
{  article s = (246, “Pen”, 20.6, 147.0);
   article *pt;
   pt = &rlargeobj(s);
   cout << pt->code << endl;
   return 0;
}
```

Classes and Objects
Classes as Arguments and Return Values

- Dynamic data structures
  - Class member can have any type
  - A member could be a pointer p pointing to another object of the same type (as the one of which p is a member)

```
struct element {int num; element *p;};
```

  - Such types, together with dynamic memory allocation, allow the creation of objects dynamically and the creation of dynamic data structures (e.g. linked lists and binary trees)

Classes and Objects
Unions

- Union is a special case of a class
  - so far, all members of class objects exist simulataneously
  - however, if we know that certain members are mutually exclusive we can save space (knowing they can never occur at the same time)
  - Unions allow class objects to share memory space
  - but it is the responsibility of the programmer to keep track of which members have been used.

  - Typically, we do this with a tag field

Classes and Objects
Unions

- Union with a tag field

```
enum choice{intflag, floatflag);
struct either_or {
   choice flag;
   union {
      int i;
      float x;
   } num;
}
...
either_or a[100];
a[k].num.i = 0;
a[k].flag = intflag;  // etc.
```

Classes and Objects
Member Functions and Encapsulation

- Member functions and encapsulation are features of C++
- With data abstraction (and abstract data types) we identify
  - the set of values a variable of a particular type can assume
  - the set of functions which can operate on variables of a particular type

Classes and Objects
Member Functions and Encapsulation

- C++ allows us to localise these definitions in one logical entity: the class
  - by allowing functions to be members of classes (i.e. through encapsulation)
  - by appropriate data hiding

Classes and Objects
Member Functions and Encapsulation

```
// VEC1: A class in which two functions are defined
// (inside the class, therefore they act as inline fns)
#include <iostream.h>

class vector {
public:
   float x, y;
   void setvec (float xx, float yy)
   {  x = xx;
      y = yy;
   }
   void printvec() const  // does not alter members
   {  cout << x << ‘ ‘ << y << endl;
   }
};
```

Classes and Objects
Member Functions and Encapsulation

```
int main()
{  vector u, v;
   u.setvec(1.0, 2.0);  // note form of function call
   u.printvec();
   v.setvec(3.0, 4.0);
   v.printvec();
   return 0;
}
```

Classes and Objects
Member Functions and Encapsulation

```
// VEC2: A class in which two functions are declared
// (but defined outside the class)
#include <iostream.h>

class vector {
public:
   float x, y;
   void setvec (float xx, float yy);
   void printvec() const;
};
```

Classes and Objects
Member Functions and Encapsulation

```
int main()
{  vector u, v;
   u.setvec(1.0, 2.0);  // note form of function call
   u.printvec();
   v.setvec(3.0, 4.0);
   v.printvec();
   return 0;
}
void vector::setvec (float xx, float yy) // note ::
   {  x = xx;
      y = yy;
   }
void vector::printvec() const
{  cout << x << ‘ ‘ << y << endl;
}
```

Classes and Objects
Member Functions and Encapsulation

- Note the use of `vector::`
  - necessary to indicate that the functions are members of the class `vector`
  - as a consequence, we can use the member identifiers (i.e. `x` and `y`)
  - could also have used `this->x` and `this->y` to signify more clearly that `x` and `y` are members of class objects.
  - `this` is a C++ keyword
  - It is always available as a pointer to the object specified in the call to that function

Classes and Objects
Member Access Control

- In both previous examples, the scope of the members x and y was global to the function in which vector was declared, i.e. main()
  - x and y could have been accessed by main()
  - this situation may not always be desired
- We would like to distinguish between class members belonging to:
  - the interface ... those that are public
  - the implementation ... those that are private (accessible only to the encapsulated functions)

Classes and Objects
Member Access Control

- Private class members are introduced by the keyword `private`
- Public class members are introduced by the keyword `public`
- The default for `structs` (i.e. no keyword provided) is `public`
- The default for `class`es is `private`

Classes and Objects
Member Access Control

```
// VEC3: A class with private members x and y

#include <iostream.h>

class vector {
public:
   void setvec (float xx, float yy);
   void printvec() const;
private:
   float x, y;
};
```

Classes and Objects

Member Access Control

```
int main()
{  vector u, v;
   u.setvec(1.0, 2.0);  // note form of function call
   u.printvec();
   v.setvec(3.0, 4.0);
   v.printvec();
   return 0;
}
void vector::setvec (float xx, float yy) // note ::
   {  x = xx;
      y = yy;
   }
void vector::printvec() const
{  cout << x << ‘ ‘ << y << endl;
}
```

Classes and Objects
Member Access Control

```
// VEC3: A class with private members x and y
// Alternative (but not recommended) declaration
#include <iostream.h>

class vector {
   float x, y; // defaults to private
public:
   void setvec (float xx, float yy);
   void printvec() const;
};
```

Classes and Objects
Member Access Control

- Using `::` for functions that return pointers
  - If we are defining a class member function outside the class
    - » e.g. `void vector::setvec()`
  - And if that function returns a pointer...
  - Then the expected `*` goes before the class name
    - » e.g. `char *vector::newvec`
  - and NOT (as might have been anticipated) after the scope resolution operator :: and before the function name
    - » e.g. `char vector::*newvec`

Classes and Objects
Constructors and Destructors

- Often, we wish an action to be performed every time a class object is created
- C++ provides an elegant way to do this:
  - Constructor ... action to be taken on creation
  - Destructor ... action to be taken on deletion
- Constructor
  - Class member function with *same name as class*
  - implicitly called whenever a class object is created (defined)

Classes and Objects
Constructors and Destructors

- Constructor
  - Class member function with *same name as class*
  - implicitly called whenever a class object is created (defined)
  - no type associated with the function (void, int, etc.)
  - must not contain return statement

Classes and Objects
Constructors and Destructors

- Destructor
  - Class member function with *same name as class preceded by a tilde ~*
  - implicitly called whenever a class object is deleted (e.g. on returning from a function where the class object is an automatic variable)
  - no type associated with the function (void, int, etc.)
  - must not contain return statement

Classes and Objects

Constructors and Destructors

```
// CONSTR: Demo of a constructor and destructor

#include <iostream.h>
class row {
public:
   row(int n=3)   // constructor with default param = 3
   {  len = n;  ptr = new int[n];
      for (int i=0; i<n; i++)
         ptr[i] = 10 * i;
   }
   ~row()         // destructor
   {  delete ptr;
   }
   void printrow(char *str) const;
private:
   int *ptr, len;
};
```

Classes and Objects

Constructors and Destructors

```
void row::printrow(char *str) const
{  cout << str;
   for (int i=0; i<len; i++)
      cout << ptr[i] << ‘ ‘;
   cout << endl;
}
void tworows();
{  row r, s(5);  // two instantiations of row,
                 // one which used default param 3
                 // one which uses 5 as the parameter
                 // Note: can’t write r();
   r.printrow(“r: “);
   s.printrow(“s: “);
}  // destructor ~row() implicitly called on exit

int main()
{  tworows();
   return 0;
}
```

Classes and Objects
Constructors and Destructors

- Default Constructor
  - Instead of providing the row() constructor with default argument:
    - » define one constructor with parameters
    - » define another constructor with no parameters, i.e. the default constructor
- If the constructor takes a parameter, then we must provide either a default constructor or a default argument

Classes and Objects

Constructors and Destructors

```
// CONSTR: Demo of a constructor and destructor

#include <iostream.h>
class row {
public:
   row(int n)   // constructor with parameters
   {  len = n;  ptr = new int[n];
      for (int i=0; i<n; i++)
         ptr[i] = 10 * i;
   }
   row()   // default constructor
   {  len = 3;  ptr = new int[3];
      for (int i=0; i<3; i++)
         ptr[i] = 10 * i;
   }
   ~row()          // destructor
   {  delete ptr;
   }
   ........
```

Classes and Objects
Constructors and Destructors

- Constructor Initializer
  - The `row()` constructor initializes the (private) class object members `len` and `ptr`
  - We can also do this another way using a constructor initializer

```
row(int n=3):len(n), ptr(new int[n])
{  for (int i=0; i<n; i++)
       ptr[i] = 10 * i;
}
```

Classes and Objects
Constructors and Destructors

- Constructors and dynamically-created objects
  - when defining class objects

    ```
    row r, s(5);
    ```

  - the constructor `row()` is invoked in the creation
  - we can also create pointers to class objects

    ```
    row *p;
    ```

  - but since this is only a pointer to `row`, the constructor is not called
  - However, if we create the `row` pointed to by `p`

    ```
    p = new row;
    ```

  - the constructor is then called.

Classes and Objects
Constructors and Destructors

- Note that the constructor `row()` is not invoked if we use `malloc();`
- Note also that the destructor `~row()` is called when we delete the row object

```
delete p;
```

- but it is NOT invoked if we use `free();`
- We can also specify arguments in the creation:

```
p = new row(5); // 5 element row
```

Classes and Objects
Constructors and Destructors

- Constructors and arrays of class objects
  - If we define an array of class objects, the constructor is called for every array element (i.e. for every class object)

```
int main()
{  row a[2], b[6]={5, 1, 2}; //how many rows?
   cout << “Array a (two elements) \n”;
   for (int i=0; i<2; i++)  {
      cout << i;
      a[i].printrow(“: “);
   }
   cout <<“\nArray b (six elements)\n”;
  for (int j=0; j<6; j++) {
      cout << j;
      b[j].printrow(“: “);
   }
}
```

What is the output?

Classes and Objects
Constructors and Destructors

- Output:

```
Array a (two elements)
0: 0 10 20
1: 0 10 20

Array b (six elements)
1: 0 10 20 30 40
2: 0
3: 0 10
4: 0 10 20
5: 0 10 20
5: 0 10 20
```

Classes and Objects
Operator Overloading and Friend Functions

- We have already seen that we can overload functions
  - must **not** have same number and type of parameters
- We can also overload operators

```
new delete
+   -   *   /   %   ^   &   |   ~
!   =   <   >   +=  -=  *=  /=  %=
^=  &=  |=  <<  >>  >>= <<= ==  !=
<=  >=  &&  ||  ++  --  ,   ->* ->
()  []
```

  - Note that the precedence of the operator cannot be changed

Classes and Objects
Operator Overloading and Friend Functions

- Example: vector addition
  - let **u** = (x_u, y_u) and **v** = (x_v, y_v)
  - the vector sum **s** = (x_s, y_s)= **u** + v is given by

    $x_s = x_u + x_v$

    $y_s = y_u + y_v$

- We will overload the addtion operator + for vectors so that we can write `s = u + v;`

Classes and Objects

Operator Overloading and Friend Functions

```
// OPERATOR: an operator function for vector addition

#include <iostream.h>
class vector {
public:
   vector(float xx=0, float yy=0)
   {  x = xx; y = yy;
   }
   void printvec()const;
   void getvec(float &xx, float &yy)const
   {  xx = x; yy = y;
   }
private:
   float x, y;
};
```

Classes and Objects

Operator Overloading and Friend Functions

```
void vector::printvec()cost
{  cout << x << ‘ ‘ << y << endl;
}

vector operator+(vector &a, vector &b) //why ref params
{  float xa, ya, xb, yb;
   a.getvec(xa, ya);
   b.getvec(xb, yb);
   return vector(xa + xb, ya + yb); // can’t write a.x
}                                   // and a.y ... why?

int main()
{  vector u(3, 1), v(1,2), s;
   s = u + v;    // sum of two vectors
   s.printvec(); // what’s the output?
   return 0;
}
```

Classes and Objects
Operator Overloading and Friend Functions

- Friend Functions
  - recall we couldn't write `a.x` and `a.y` in `operator+` because the members `x` and `y` are private to the class object (and `operator+` is not a class member)
  - consequently we had to have the class member function `getvec()`
  - we can allow `operator+` (and other functions) access to the private members
    - » by defining it as a `friend` function (next)
    - » by having it as a class member function (second next)

Classes and Objects

Operator Overloading and Friend Functions

```
// FRIEND: the ‘friend’ keyword applied to an operator
//         function

#include <iostream.h>
class vector {
public:
   vector(float xx=0, float yy=0)
   {  x = xx; y = yy;
   }
   void printvec()const;
   friend vector operator+(vector &a, vector &b);
private:
   float x, y;
};
```

Classes and Objects

Operator Overloading and Friend Functions

```
void vector::printvec()cost
{  cout << x << ‘ ‘ << y << endl;
}

vector operator+(vector &a, vector &b)
{
   return vector(a.x + b.x, a.y + b.y); //friend access
}

int main()
{  vector u(3, 1), v(1,2), s;
   s = u + v;    // sum of two vectors
   s.printvec(); // what’s the output?
   return 0;
}
// NOTE: operator+ is a friend function but NOT a class
  member
```

Classes and Objects

Operator Overloading and Friend Functions

```
// FRIEND: the ‘friend’ keyword applied to an operator
//         function
//         This time, define operator+ in the class

#include <iostream.h>
class vector {
public:
   vector(float xx=0, float yy=0)
   {  x = xx; y = yy;
   }
   void printvec()const;
   friend vector operator+(vector &a, vector &b)
   {
      return vector(a.x + b.x, a.y + b.y);
   };
private:
   float x, y;
};
```

Classes and Objects
Operator Overloading and Friend Functions

- Operators as member functions
  - we can also allow `operator+` access to the private members
    - » by defining it as a class member
    - » however, the syntax is a little odd!
    - » operator+ is a binary operator but it is allowed have only one parameter (the second operand)
      - the first operand is accessed implicitly and directly

Classes and Objects

Operator Overloading and Friend Functions

```
// OPMEMBER: An operator function as a class member

#include <iostream.h>

class vector {
public:
   vector(float xx=0, float yy=0)
   {  x = xx; y = yy;
   }
   void printvec()const;
   vector operator+(vector &b);
private:
   float x, y;
};
```

Classes and Objects

Operator Overloading and Friend Functions

```
void vector::printvec()cost
{  cout << x << ‘ ‘ << y << endl;
}

vector vector::operator+(vector &b)
{
   return vector(x + b.x, y + b.y);//first operand is
}                                  //the vector for
                                   //which the function
int main()                         //is called
{  vector u(3, 1), v(1,2), s;
   s = u + v;    // sum of two vectors
   s.printvec(); // what’s the output?
   return 0;
}
```

Classes and Objects
Operator Overloading and Friend Functions

- in effect

```
s = u + v;
```

is equivalent to

```
s = u.operator+(v);
```

which is why there is only one operand for a binary operator!

Classes and Objects
Operator Overloading and Friend Functions

- Note that we are not always free to choose between a member function and a friend function for operator overloading:
- C++ requires that the following operators can only be overloaded using member functions (we cannot define friend functions for them)

```
=,  [],  (),  ->
```

Classes and Objects
Operator Overloading and Friend Functions

- Overloading applied to unary operators
  - Define the minus sign as the unary operator for vectors:

```
vector u, v;
...
v = -u;
```

  - and, from which, we can then proceed to define a binary minus operator since:

```
a - b = a + (-b)
```

Classes and Objects

Operator Overloading and Friend Functions

```
// UNARY: An unary operator, along with two binary ones

#include <iostream.h>

class vector {
public:
   vector(float xx=0, float yy=0)
   {  x = xx; y = yy;
   }
   void printvec()const;
   vector operator+(vector &b); // binary plus
   vector operator-();          // unary minus
   vector operator-(vector &b); // binary minus

private:
   float x, y;
};
```

Classes and Objects

Operator Overloading and Friend Functions

```
void vector::printvec()cost
{  cout << x << ‘ ‘ << y << endl;
}

vector vector::operator+(vector &b) // Binary plus
{
   return vector(x + b.x, y + b.y);
}

vector vector::operator-() // Unary minus
{
   return vector(-x, -y);
}

vector vector::operator-(vector &b) // Binary minus
{
   return *this + -b; // recall ‘this’ is a pointer to
}                     // the current object
```

Classes and Objects

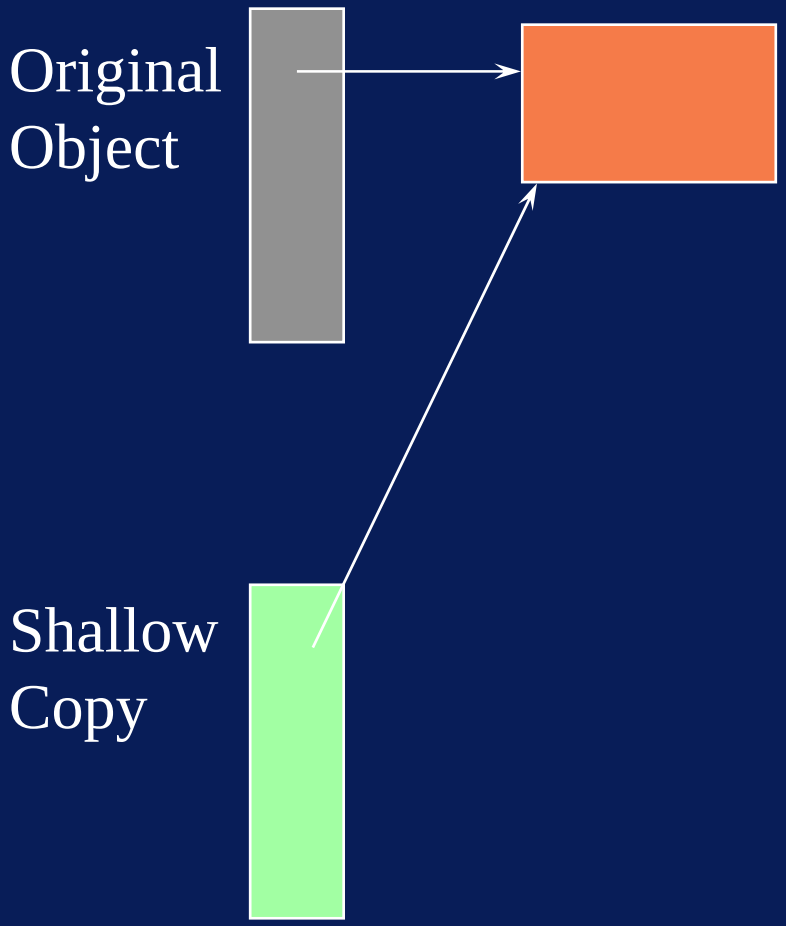
Operator Overloading and Friend Functions

```
int main()
{  vector u(3, 1), v(1,2), sum, neg, diff;
   sum = u + v;
   sum.printvec();  // what's the output?
   neg = -sum;
   neg.printvec();  // what's the output?
   diff = u - v;
   diff.printvec(); // what's the output?
   return 0;
}
```

Classes and Objects
Copying a Class Object

- A class object that contains a pointer to dynamically allocated memory can be copied in two ways:
  - Shallow copy
    - » where the class contains only member functions and ‘simple’ data members (which are not classes)
    - » copying is by default done ‘bitwise’
      - all members, including the pointers, are copied literally

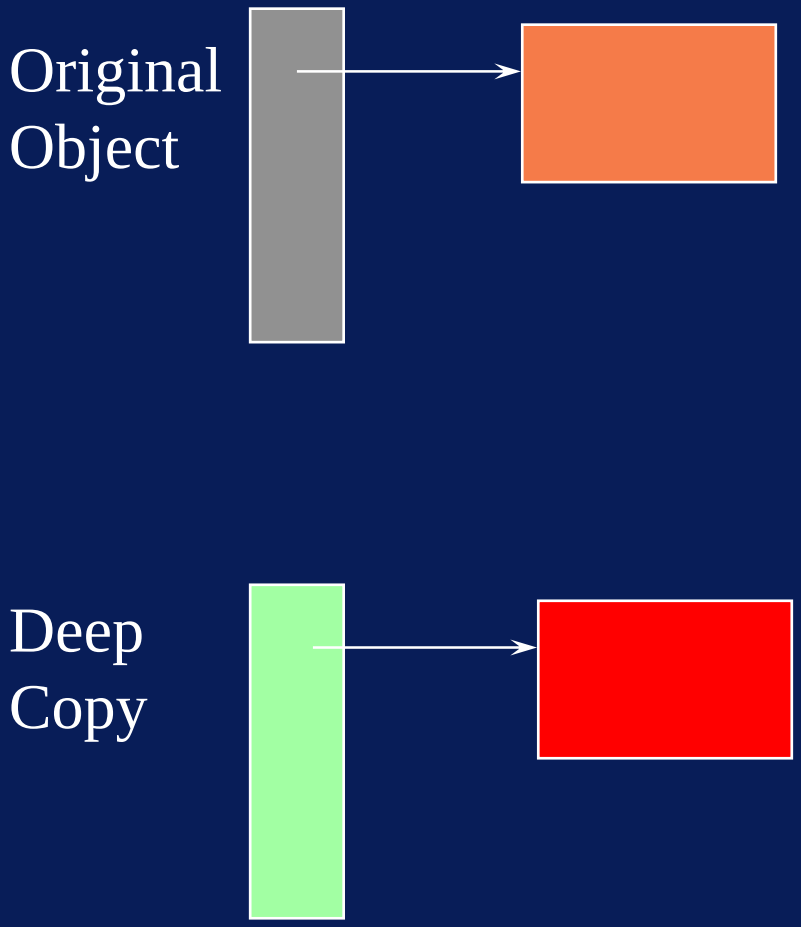
Classes and Objects
Copying a Class Object



Classes and Objects
Copying a Class Object

- A class object that contains a pointer to dynamically allocated memory can be copied in two ways:
  - Deep copy
    - » all members are copied
    - » but the pointer and the data to which it points are replicated

Classes and Objects
Copying a Class Object



Classes and Objects
Copying a Class Object

- The difference between deep and shallow copies is important when the referenced memory is allocated by a constructor and deleted by a destructor
  - why?
  - because the shallow copies will also be effectively deleted by the destructor (and, anyway, attempting to delete the same thing twice is dangerous and illegal)

Classes and Objects
Copying a Class Object

- If we require deep copies, then we must take care to define the constructors and assignments appropriately
- Typically, we will define a copy constructor as a (function) member of a class for copying operations other than by assignment
  - This copy constructor will be declared in the following way:

```
class_name(const class_name &class_object);
```

  - parameter is always a reference parameter

Classes and Objects
Copying a Class Object

- For copying by assignment, we must define an assignment operator to prevent shallow copying

```
class_name operator=(class_name class_object);
```

Object-Oriented Programming

- Object-oriented programming - many definitions
  - exploitation of class objects, with private data members and associated access functions (cf. concept of an abstract data type)
  - However, Ellis and Stroustrup give a more limited meaning:

    ‘The use of derived classes and virtual functions is often called object-oriented programming’

    So, we need some more C++!

Object-Oriented Programming
Interface, Implementation, and Application Files

- Preferred practice for programs dealing with classes: 3 files
  - Interface
    - » between implementation and application
    - » Header File that declares the class type
    - » Functions are declared, not defined (except inline functions)
  - Implementation
    - » `#includes` the interface file
    - » contains the function definitions
  - Application ...

Object-Oriented Programming
Interface, Implementation, and Application Files

- Preferred practice for programs dealing with classes: 3 files
  - Interface
  - Implementation
  - Application
    - » `#includes` the interface file
    - » contains other (application) functions, including the `main` function

Object-Oriented Programming
Interface, Implementation, and Application Files

- When writing an application, we are class users
  - don’t want to know about the implementation of the class (c.f ADTs)
  - Thus, the interface must furnish all the necessary information to use the class
  - Also, the implementation should be quite general (cf. reusability)

Object-Oriented Programming
A Class for Sets

- Required data type: sets of integers
- Required functions:
  - declaration, e.g.
    `iset S, T=1000, U=T, V(1000);`
    - » `S` should be empty
    - » `T`, `U`, and `V` should contain just one element (1000)
  - adding an element, e.g.
    `S += x`
  - removing an element, e.g.
    `S -= x`
    - » must be valid even if `x` is not an element of `S`

Object-Oriented Programming
A Class for Sets

- Required data type: sets of integers
- Required functions:
  - Test if an element is included in the set, e.g.
    `if (S(x)) ... // is x in set X`
  - Display all elements in increasing order, e.g.
    `S.print();`
  - Set assignment, e.g.
    `T = S`

Object-Oriented Programming
A Class for Sets

- Required data type: sets of integers
- Required functions:
  - Inquiring about the number of elements by converting to type int, e.g.
    ```
    cout << “S contains “ << int(S) << “elements”;
    ```
  - Inquiring if the number of elements in the set is zero, e.g.
    ```
    if (S==0) ....
    if (!S) ....
    ```

Object-Oriented Programming
A Class for Sets

- Note that we have NOT specified how the set is to be represented or implemented (again, cf. ADTs)

Object-Oriented Programming
A Class for Sets - Application

```
// SETAPPL:  Demonstration program for set operations
//           (application; file name: setappl.cpp)

#include “iset.h”

int main()
{  iset S=1000, T, U=S;
   if (!T) cout << “T is empty.\n”;
   if int(U) cout << “U is not empty.\n”;
   S += 100;  S += 10000;
   (((s += 10) +=1) += 20) += 200;
   cout << “There are “ << int(S) << “elements in S\n”;
   T += 50;  T += 50;
   cout << “S: “; S.print();
   S -= 1000; cout <<“1000 removed from S\n”;
   if (S(1000))
      cout << “1000 belongs to S (error)\n”;
   else
      cout << “1000 is no longer in S\n”);
```

Object-Oriented Programming
A Class for Sets - Application

```
    if (S(100))
       cout << “100 still belongs to s\n”;
    cout << “S: “; S.print();
    cout << “T: “; T.print();
    cout << “U: “; U.print();
    T = S;
    cout << “After assigning S to T, we have T: “;
    T.print();
    return 0;
}
```

Object-Oriented Programming
A Class for Sets - Application

```
Expected output

T is empty
U is not empty
There are 7 elements in S
S: 1 10 20 100 200 1000 10000
1000 removed from S
1000 is no longer in S
100 still belongs to S
S: 1 10 20 100 200 10000
T: 50
U: 1000
After assigning S to T, we have T:1 10 20 100 200 10000
```

Object-Oriented Programming
A Class for Sets - Application

```
// ISET.H:  Header file for set operations
//          (interface; file name: iset.h)

#include “iostream.h”

class iset {
public:
   iset()                       // constructor to begin
   {  a = NULL;                 // with empty set
      n = 0;
   }
   iset(int x)                  // constructor to begin
   {  a = NULL;                 // with one element x
      *this += x;
      n = 1;
   }
   ~iset()                      // destructor
   {  delete[] a;
   }
```

Object-Oriented Programming
A Class for Sets - Application

```
    iset &operator+=(int x); // adds x to the set
    iset &operator-=(int x); // removes x from the set
    int operator()(int x) const; // is x in the set?
    void print() const;      // prints all elements of
                             // the set on one line
    iset &operator=(iset S); // assignment operator
    iset (const iset &S);    // copy constructor NB
    operator int()           // convert iset to int
    {  return n;
    }
private:
    int n, *a;
}
```

Object-Oriented Programming
A Class for Sets - Application

```
// ISET:  Implementation file for set operations;
//        (implmentation; file name: iset.cpp)
// Note:
// using a relatively inefficient array representation

#include “iset.h”

const int blocksize=5;  // may be replaced with larger
                        // value
```

Object-Oriented Programming
A Class for Sets - Application

```
static int *memoryspace(int *p0, int n0, int n1)

/* if p0 == NULL, allocate an area for n1 integers   */
/* if p0 != NULL, increase or decrease old sequence  */
/* p0[0], ... , p[n0-1]                              */
/* in either case, the resulting new sequence is     */
/* p1[0], ..., p1[n1-1], and p1 is returned          */

{  int *p1 = new int[n1];
   if (p0 != NULL) // copy from p0 to p1:
   {  for (int i=(n0<n1?n0:n1)-1; i>=0; i--)
         p1[i] = p0[i];
      delete p0;
   }
   return p1;
}
```

Object-Oriented Programming
A Class for Sets - Application

```
int binsearch(int x, int *a, int n)

/* The array a[0], ... , a[n-1] is searched for x
   Return value:
      0 if n == 0 or x <= a[0]
      n if x > a[n-1]
      i if a[i-1] < x <= a[i]
*/

{  int m, l, r;
   if (n == 0 || x <= a[0]) return 0;
   if (x > a[n-1]) return n;
   l = 0; r = n-1;
   while (r - l > 1)
   {  m = (l + r)/2;
      (x <= a[m] ? r : l) = m;  // ouch! real C!
   }
   return r;
}
```

Object-Oriented Programming
A Class for Sets - Application

```
iset &iset::operator+=(int x)
{  int i=binsearch(x, a, n), j;  // !!
   if (i >= n || x != a[i]) // x is not yet in set?
   {  if (n % blocksize == 0)
         a = memoryspace(a, n, n+ blocksize);
      for (j=n; j>i; j--)
         a[j] = a[j-1];
      n++;
      a[i] = x;
   }
   return *this;
}
```

Object-Oriented Programming
A Class for Sets - Application

```
iset &iset::operator-=(int x)
{  int i=binsearch(x, a, n), j;  // !!
   if (i < n && x == a[i])
   {  n--;
      for (j=i; j<n; j++)
         a[j] = a[j-1];
      if (n % blocksize == 0)
         a = memoryspace(a, n+1, n);  // release one
   }                                   // block
   return *this;
}
```

Object-Oriented Programming
A Class for Sets - Application

```
void iset::print() const
{  int i;
   for (i=0; i<n; i++)
      cout << a[i] << " ";
}

void iset::operator()(int x) const
{  int i=binsearch(x, a, n);
   return i < n && x == a[i];
}

static int *newcopy(int n, int *a)
// copy a[0], ..., a[n-1] to a newly allocate area
// and return the new start address
{  int *p = new int[n];
   for (int i=0; i<n; i++)
      p[i] = a[i];
   return p;
}
```

Object-Oriented Programming
A Class for Sets - Application

```
iset &iset::operator=(iset S) // assignment operator
{  delete a;
   n = S.n;
   a = newcopy(n, S.a);
   return *this;
}

iset::iset(const iset &S) // copy constructor
{  n = S.n;
   a = newcopy(n, S.a);
}
```

Object-Oriented Programming
Exercises

13. Implement and test `iset` class as defined

Object-Oriented Programming
Derived Classes and Inheritance

- Given a class B, we can derive a new one D
  - comprising all the members of B
  - and some new ones beside
- we simply refer to B in the declaration of D
  - B is called the base class
  - D is called the derived class
- the derived class inherits the members of the base class

Object-Oriented Programming
A Class for Sets - Application

```
/* Consider the new class object geom_obj  */

#include  <iostream.h>

class geom_obj {
public:
   geom_obj(float x=0, float y=0): xC(x), yC(y){}
   void printcentre() const
   {  cout << xC << " " << yC << endl;
   }
protected:    // new keyword
   float xC, yC;
};


/* not a lot we can do with this class as it stands */
/* we wish to extend it to deal with circles and    */
/* squares                                          */
```

Object-Oriented Programming
A Class for Sets - Application

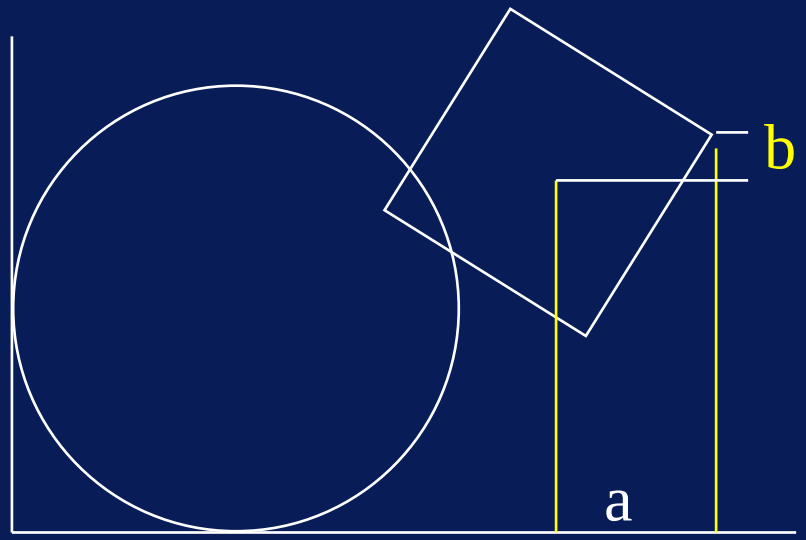
```
/* define derived class objects circle and square */

class circle: public geom_obj {  // base class
public:                          // inherit all public
   circle(float x_C, float y_C, float r)
      : geom_obj(x_C, y_C)
   { radius = r;
   }
   float area() const
   {  return PI * radius * radius;
   }
private:
   float radius;
};
```

Object-Oriented Programming
A Class for Sets - Application

```
/* define derived class objects circle and square */
/* square defined by its centre and vertex        */
class square: public geom_obj {  // base class
public:                          // inherit all public
   square(float x_C, float y_C, float x, float y)
      : geom_obj(x_C, y_C)
   {  x1 = x;
      y1 = y;
   }
   float area() const
   {  float a, b;
      a = x1 - xC; b = y1 - yC;
      return 2 * (a * a + b * b);
   }
private:
   float x1, y1;
};
```

Object-Oriented Programming
Derived Classes and Inheritance



Object-Oriented Programming
Derived Classes and Inheritance

- `circle` and `square` are extensions of their base class `geom_obj`
- the keyword public used in the declaration specifies that all public members of the base class `geom_obj` are also regarded as public members of the derived class
  - class `square` is publicly derived from `geom_obj`

```
square S(3, 3.5, 4.37, 3.85);
S.printcentre();
```

    - » printcentre() is a public class member function of geom_obj

Object-Oriented Programming
Derived Classes and Inheritance

- `xc` and `yc` are protected members of the base class `geom_obj`
- but they are used in the area member function of square
- protected members are similar to private ones
  - except that a derived class has access to protected members of its base class
  - a derived class does not have access to private members of its base class

Object-Oriented Programming
Derived Classes and Inheritance

- User-defined assignment operators
  - if an assignment operator is defined as a member function of a base class, it is not inherited by any derived class

Object-Oriented Programming
Derived Classes and Inheritance

- Constructors and destructors of derived and base classes
  - When an object of (derived) class is created
    - » the constructor of the base class is called first
    - » the constructor of the derived class is called next
  - When an object of a (derived) class is destroyed
    - » the destructor of the derived class is called first
    - » the destructor of the base class is called next

Object-Oriented Programming
Derived Classes and Inheritance

- Constructors and destructors of derived and base classes
  - We can pass arguments from the constructor in a derived class to the constructor of its base class
    - » normally do this to initialize the data members of the base class
    - » write a constructor initializer

```
class square: public geom_obj {
public:
   square(float x_C, float y_C, float x,float y)
      : geom_obj(x_C, y_C)  // con. init.
```

Object-Oriented Programming
Derived Classes and Inheritance

- since the geom_obj constructor has default arguments, this initializer is not obligatory here
- if we omit it, the constructor of geom_obj is called with its default argument values of 0
- however, the initializer would really have been required if there had been no default arguments, i.e. if we had omitted the `=0` from the constructor:

```
class geom_obj {
public:
   geom_obj(float x=0, float y=0): xC(x), yC(y){}
```

Object-Oriented Programming

Derived Classes and Inheritance

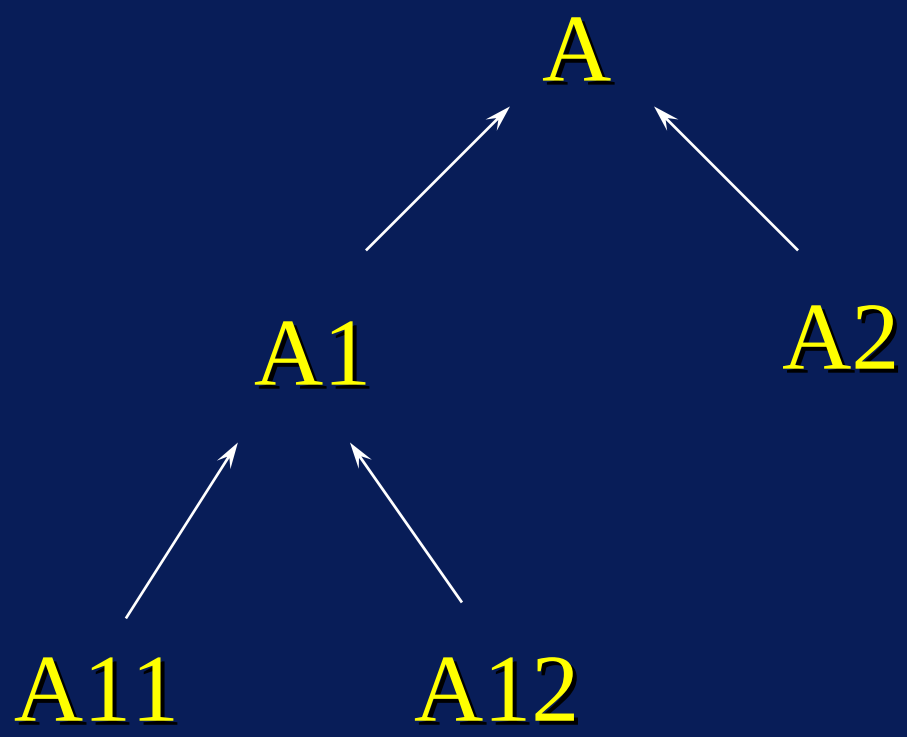
```
int main()
{  circle C(2, 2.5, 2);
   square S(3, 3.5, 4.37, 3.85);
   cout << “Centre of circle: “; C.printcentre();
   cout << “Centre of square: “; S.printcentre();
   cout << “Area of circle:   “ << C.area() << endl;
   cout << “Area of square:   “ << S.area() << endl;
   return 0;
}

/* output */

Centre of circle: 2 2.5
Centre of square: 3 3.5
Area of circle:   12.5664
Area of square:   3.9988
```

Object-Oriented Programming

Derived Classes and Inheritance



A tree of (derived) classes

Object-Oriented Programming
Derived Classes and Inheritance

- Conversion from derived to base class
  - allowed: conversion from derived to base class
  - NOT allowed: conversion from base to derived
  - Same applies to corresponding pointer types
  - why? derived class objects may contain members that do not belong to the base class

Object-Oriented Programming

Derived Classes and Inheritance

```
/* code fragments to illustrate legal and illegal */
/* class conversions                               */

class B {...};           // base class B
class D: public B{ ...} // derived class D
...
B b, *pb;
D d, *pd;
...
b = d;      // from derived to base: OK
pb = pd;    // corresponding pointer types: OK
d = b;      // from base to derived: error
d = (D)b;   // even with a cast: error
pd = pb;    // corresponding pointer types: error
pd = (D*)b; // with cast: technically OK but suspicious
```

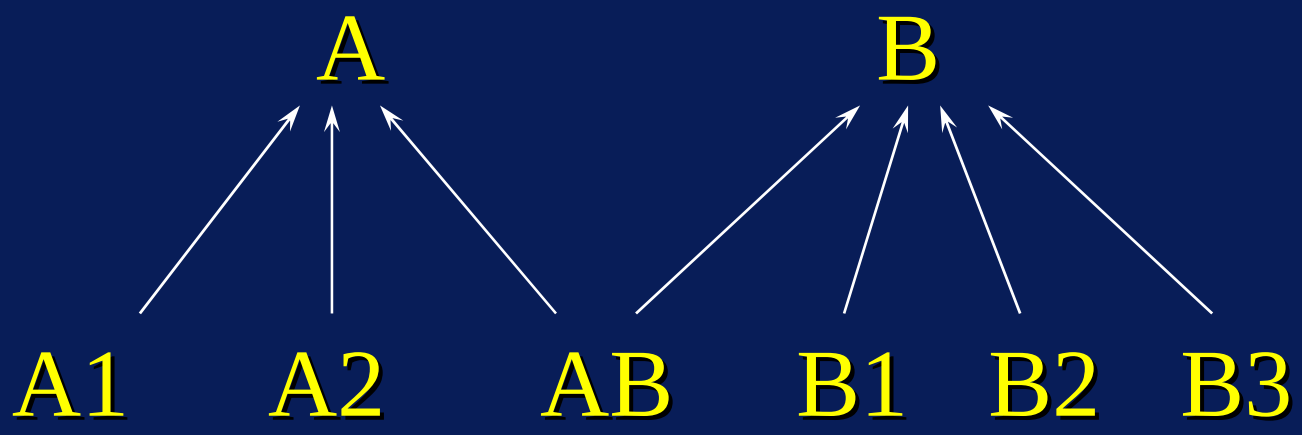
Object-Oriented Programming
Derived Classes and Inheritance

- Multiple inheritance
  - a class can be derived from more than one base class
    - » C++ Release 2

```
class A {...}; // base class A
class B {...}; // base class B
class AB: public A, public B {
...
}
```

Object-Oriented Programming

Derived Classes and Inheritance



Multiple Inheritance

Object-Oriented Programming
Derived Classes and Inheritance

- Multiple inheritance
  - If AB has a constructor with parameters, we can pass these to each base class:

```
class AB {
public:
   AB(int n=0, float x=0, char ch='A')
      :A(n, ch), B(n, x)
{ ...
}
```

  - The creation of an object of class AB causes the three constructors for A, B, and AB, in that order, to be called.

Object-Oriented Programming
Virtual Functions and Late Binding

- Suppose we have declared class `ctype` as follows:

```
class ctype {
public:
   virtual void f()
   { ...
   }
   ...
};
```

  - the keyword `virtual` is important if
    - » ctype has derived classes, e.g. ctype1 and ctype2, (i.e. it is a base class for derived classes ctype1 and ctype2)
    - » and we are using pointers to class objects

Object-Oriented Programming
Virtual Functions and Late Binding

- If we define only a pointer to the class and create the class object dynamically

```
ctype *p;
...
p = new ctype;
```

  - the `ctype` object `*p` created in this way is only loosely related to `p`
    - » `p` can also point to the other `ctype` objects

Object-Oriented Programming
Virtual Functions and Late Binding

- Let's declare two derived classes

```
class ctype1: public ctype {
public:
   void f() {...}
   ...
};

class ctype2: public ctype {
public:
   void f() {...};
};

ctype *p
```

Object-Oriented Programming
Virtual Functions and Late Binding

- since conversion of pointer to derived class to pointer to base class is allowed we can have:

```
p = new ctype1

/* or */

p = new ctype2
```

- the three class types `ctype`, `ctype1`, and `ctype2` have member functions with the same name (`f`)
  - `f` is a virtual function

Object-Oriented Programming
Virtual Functions and Late Binding

- `f()` is a virtual function
  - given the function call

    ```
    p->f()
    ```

  - the decision as to which if the three possible functions

    ```
    ctype::f
    ctype1::f
    ctype2::f
    ```

  - is made at run-time on the basis of type of object pointed to by `p`

Object-Oriented Programming
Virtual Functions and Late Binding

- This run-time establishment of the link between the function `f` and the pointer `p` is called
  - late binding
  - dynamic binding

Object-Oriented Programming
Virtual Functions and Late Binding

- If the keyword `virtual` had been omitted from the definition of `f` in declaration of `ctype`
- only the type of `p` would have been used to decide which function to call, *i.e.*,
  `ctype::f` would have been called
- This establishment of the link between the function `f` and the pointer `p` is made at compile time and is called
  - early binding
  - static binding

Object-Oriented Programming

Virtual Functions and Late Binding

```
// VIRTUAL: A virtual function in action

#include <iostream.h>

class animal {
public:
   virtual void print() const
   {  cout << “Unknown animal type\n”;
   }
protected:
   int nlegs;
};
```

Object-Oriented Programming

Virtual Functions and Late Binding

```
class fish: public animal {
public:
   fish(int n)
   { nlegs = n;
   }
   void print() const
   {  cout << “A fish has “ << nlegs << “ legs\n”;
   }
};
```

Object-Oriented Programming

Virtual Functions and Late Binding

```
class bird: public animal {
public:
   bird(int n)
   { nlegs = n;
   }
   void print() const
   {  cout << “A bird has “ << nlegs << “ legs\n”;
   }
};
```

Object-Oriented Programming

Virtual Functions and Late Binding

```
class mammal: public animal {
public:
   mammal(int n)
   { nlegs = n;
   }
   void print() const
   {  cout << “A mammal has “ << nlegs << “ legs\n”;
   }
};
```

Object-Oriented Programming

Virtual Functions and Late Binding

```
int main()
{  animal *p[4];
   p[0] = new fish(0);
   p[1] = new bird(2);
   p[2] = new mammal(4);
   p[3] = new animal;
   for (int i=0; i<4; i++)  // key statement
      p[i]->print();        // which print is called?
   return 0;                //   fish::print
}                           //   bird::print
                            //   mammal::print
                            //   animal::print
                            // the choice is made at
                            // run-time
```

Object-Oriented Programming

Virtual Functions and Late Binding

```
/* output */

A fish has 0 legs
A bird has 2 legs
A mammal has 4 legs
Unknown animal type
```

- If print had not been defined as virtual, the binding would have been early (static ... at compile time) and the fourth output line would have been printed four times

Object-Oriented Programming
Virtual Functions and Late Binding

- Object-Oriented Programming
  - the use of virtual functions and derived classes
- The style of programming is also called Polymorphism
  - objects of different (derived) types
  - are accessed in the same way
- Member functions are sometimes called methods
  - calling an object's member function is referred to as sending a message to an object

Object-Oriented Programming
Virtual Functions and Late Binding

- Suppressing the virtual mechanism
  - in the following function call
    ```
    p[1]->print();
    ```
  - the function calls the print function for the derived class bird
  - we can over-ride this with the scope resolution operator
    ```
    p[1]->animal::print();
    ```
  - in which case the function calls the print function for the derived class animal

Object-Oriented Programming
Virtual Functions and Late Binding

- Pure virtual functions and abstract classes
  - We can declare the function `print` in the base class as a pure virtual function by writing
    ```
    virtual void print() const = 0;
    ```
  - This has some important consequences
    - » the base class now becomes an abstract class
    - » an abstract class cannot be used to create objects (or this type)
    - » they can only be used for the declaration of derived classes

Object-Oriented Programming
Virtual Functions and Late Binding

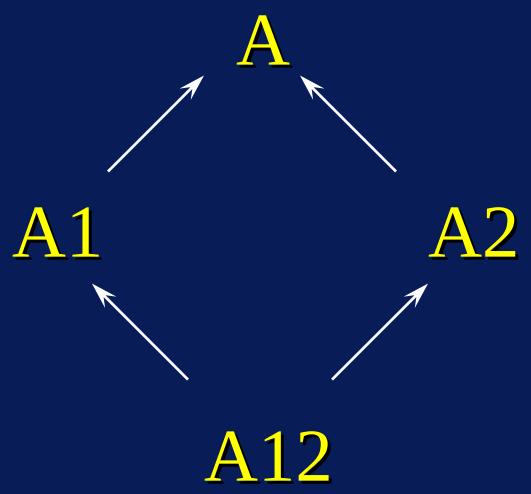
- Pure virtual functions and abstract classes
  - » So, for example, the following are illegal:

```
p[3] = new animal;// error
animal A;         // error
```

  - – Making the base class animal abstact makes it impossible to omit any of the print functions in the derived classes

Object-Oriented Programming
Virtual Functions and Late Binding

- Virtual base classes
  - assume we have a base class A
  - and derived classes A1 and A2
  - and a further derived class A12 with multiple inheritance



Object-Oriented Programming
Virtual Functions and Late Binding

- Virtual base classes
  - If base class A had a member a, then
  - Derived class A12 will inherit two members called a (one through A1 and one through A2)
  - Such duplication of indirectly inherited members can be suppressed by using the keyword virtual in the declarations of A1 and A2

```
class A { ... };
class A1: virtual public A { ... };
class A2: virtual public A { ... };
class A12: public A1, public A2 { ... };
```

Object-Oriented Programming
Virtual Functions and Late Binding

- Virtual base classes
  - A derived class cannot directly inherit the members of a base class more than once

```
class A12: public A, public A2 { ... };
// error
```

Object-Oriented Programming
Static Class Members

- Static data members
  - Normally, a data member of a class type is stored in every object of that type
  - If we use the keyword static for a class data member, however, there will be only one such member for the class, regardless of how many objects there are
    - » a static class member belongs to its class type rather than to the individual ojects of that type

Object-Oriented Programming
Static Class Members

- Static member functions
  - cannot use any data members that are specific for objects
  - the this pointer is not available in static member functions

Object-Oriented Programming
Static Class Members

```
/* STATMEM: Using a static class member to count
            how many times the constructor person()
            is called                                */

#include <iostream.h>
#include <string.h>

class person {
public:
   person (char *str)
   {  strcpy(name, str);
      count++;   // increment the static counter
   }
   void print() const
   {  cout << name << endl;
   }
```

Object-Oriented Programming
Static Class Members

```
    static void printcount()  // static function member
    {  cout << “There are “ << count
            << “ persons.” << endl;
    }
private:
    char name[20];
    static int count;  // static data member
};

int person::count=0; // must define (instantiate) the
                     // count member
int main()
{  person A(“Mary”), B(“Ciana”), C(“Georgina”), *p;
    p = new person(“Brighid”);
    A.print(); B.print(); C.print(); p->print();
    person::printcount();
    return 0;
}
```

Object-Oriented Programming
Static Class Members

```
the output is as follows:

Mary
Ciana
Georgina
Brighid
There are 4 persons.
```

Object-Oriented Programming
Static Class Members

- Static member functions - key points
  - must define a static class member outside the class definition (to instantiate the member)

```
int person::count=0
```

  - since the static class member is associated with the class and not the object, we must reference the member with the class name and not an object name

```
person::count
person::printcount()
```

Object-Oriented Programming
Pointers to Members

- To use pointers to class member functions
  - use the class name
  - followed by ::
  - as a prefix to the declaration of the pointer
  - which will point to the required class member function

Object-Oriented Programming
Static Class Members

```
class example {
public:
   example (int ii, int jj):i(ii), j(jj) {}
   int ivalue(){return i;}
   int jvalue(){return j;}
private:
   int i, j;
};

int (example::*p)(); // pointer to a member function in
                     // class example (no parameters
                     // and returning int
example u(1,2);
...

p = example::ivalue;
cout << (u.*p)();  // call *p for u ... output is 1
```

Object-Oriented Programming
Polymorphism and Reusability

- Example to demonstrate the power and efficiency of object-oriented programming
  - Heterogeneous linked-list of geometric shapes
  - Begin with circles and lines
  - Extend to triangles
  - Use virtual function `print`
  - in an abstract class `element` from which we will derive the appropriate class for each geometry
    - » Lines: defined by two end points
    - » Circles: defined by centre and radius

Object-Oriented Programming

Polymorphism and Reusability

```
/* FIGURES.H: interface file to build linked-list   */
/*            for lines and circles                 */

#include <iostream.h>
#include <stdio.h>

class point {
public:
   float x, y;
   point(float xx=0, float yy=0):x(xx), y(yy) {}
}

class element {                    // abstract class
public:
   element *next;
   virtual void print() const=0; // pure virtual fn.
}
```

Object-Oriented Programming

Polymorphism and Reusability

```
class line: public element {
public:
   line (point &P, point &Q, element *ptr);
   void print() const;
private:
   point A, B;
};

class circle: public element {
public:
   circle (point &center, float radius, element *ptr);
   void print() const;
private:
   point C;
   float r;
};
void pr(const point &P, const char *str=“, “);
```

Object-Oriented Programming

Polymorphism and Reusability

```
// FIGURES: Implementation file (figures.cpp) for
//          linked lists of circles and lines

#include “figures.h”

line::line(point &P, point &Q, element *ptr)
{  A = P;
   B = Q;
   next = ptr;
}

void line::print() const
{  cout << “Line: “;
   pr(A); pr(B, “\n”);
}
```

Object-Oriented Programming

Polymorphism and Reusability

```
circle::circle(point &center, float radius,
               element *ptr);
{  C = center;
   r = radius;
   next = ptr;
}

void circle::print() const
{  cout << “Circle: “;
   pr(C);
   cout << r << endl;
}

void pr(const point &P, const char *str)
{  cout << “(“<< P.x << “, “<< P.y << “)”<< str;
}
```

Object-Oriented Programming

Polymorphism and Reusability

```
// FIGURES: sample application file

#include “figures.h”

int main()
{  element *start=NULL;
   start = new line(point(3,2), point(5,5)), start);
   start = new circle(point(4,4), 2, start);
}
```

Object-Oriented Programming

Polymorphism and Reusability

- Some time later, we may wish to add a triangle type to our systems
- We then write a new interface file
- and a new implementation

Object-Oriented Programming

Polymorphism and Reusability

```
/* TRIANGLE.H: adding a triangle (interface file)   */
/*     Class triangle is derived from class element */

class triangle: public element {
public:
   triangle(point &P1, point &P2, point &P3,
            element *ptr);
   void print() const;
private:
   point A, B, C;
}
```

Object-Oriented Programming

Polymorphism and Reusability

```
// TRIANGLE: adding a triangle class
//           (implementation file for triangle.cpp)

#include “figures.h”
#include “triangle.h”

triangle::triangle(point &P1, point &P2, point &P3,
                   element *ptr)
{  A = P1;
   B = P2;
   C = P3;
   next = ptr;
}

void triangle::print() const
{  cout << “Triangle: “;
   pr(A); pr(B); pr(C, “\n”);
}
```

Object-Oriented Programming

Polymorphism and Reusability

- Later again, we may wish to add the ability to distinguish between lines of different thickness
- Instead of deriving a new class from the base class `element`, we can derive one from the class `line` for example `fatline`
- We then write a new interface file
- and a new implementation

Object-Oriented Programming

Polymorphism and Reusability

```
/* FATLINE.H: additional interface file for fat lines*/

class fatline: public line {
public:
   fatline(point &P, point &Q, float thickness,
            element *ptr);
   void print() const;
private:
   float w;
}
```

Object-Oriented Programming

Polymorphism and Reusability

```
// FATLINE: Implementation file (fatline.cpp) for
//          for thick lines

#include “figures.h”
#include “fatline.h”

fatline::fatline(point &P, point &Q, float thickness,
                 element *ptr): line(P, Q, ptr)
                    // note the constructor initializer
{  w = thickness;
}

void fatline::print() const
{  this->line::print();
   cout << “   Thickness: “ << w << endl;
}
```

Object-Oriented Programming

Polymorphism and Reusability

```
// DEMO: This program builds a heterogeneous linked
//       list in which data about a line, a circle,
// a triangle, and a ‘fat’line are stored
// To be linked with FIGURES, TRIANGLE, and FATLINE

#include “figures.h”
#include “triangle.h”
#include “fatline.h”

int main()
{  element *start=NULL, *p;
// Build a heterogeneous linked list
start = new line(point(3, 2), point(5, 5), start);
start = new circle(point(4, 4), 2, start);
start = new triangle(point(1, 1), point(6, 1),
                     point(3, 6), start);
start = new fatline(point(2, 2), point(3, 3), 0.2, start);
```

Object-Oriented Programming

Polymorphism and Reusability

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                     point(3, 6), start);
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```

Object-Oriented Programming

Polymorphism and Reusability

```
   for (p=start; p!=NULL; p = p->next)
      p->print(); // polymorphic data handling and
                  // late binding!
}
```

Object-Oriented Programming
Exercises

14. Modify (and test) the `iset` class as follows
    - replace the element addition `+=` with the addition operator `+`
      ```
      S = S + x;
      ```
    - replace the element removal `-=` with the assignment operator `-`
      ```
      S = S - x;
      ```
    - replace the null set check with the function `isempty();`
    - add a set union operator `+`
    - add a set intersection operation `*`

Object-Oriented Programming
Exercises

15. Modify (and test) the `iset` class as follows
    - add a function null which removes all elements from the set and returns an empty set
    - replace the inclusion operator `S(x)` with the function `contains()` returning TRUE or FALSE

Object-Oriented Programming
Exercises

16. Modify (and test) the `iset` class
    - represent the set with a linear linked list and do insertions with an insertion sort
    - represent the set with a binary tree

Object-Oriented Programming
Exercises

17. Create a new set class for character strings
    `string_set`